NOISE LEVELS FROM OPERATIONS OF CTA RAIL TRANSIT TRAINS

PREPARED FOR

CHICAGO TRANSIT AUTHORITY

MAY 1977

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MAY 1977

SUBMITTED TO:

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I. INTRODUCTION

This report presents the results of an extensive study of the noise generated by Chicago Transit Authority rail rapid transit vehicles operating on the various types of way structures which comprise the CTA rail transit system. The measurements have included evaluation of car interior noise levels, station platform noise levels, and wayside noise levels for transit train operations on elevated structure, on ballast and tie track, and in subways. The objective of the study was to provide for evaluation of the noise and vibration characteristics of the CTA vehicles and facilities and to determine possible procedures for reducing the noise exposure for patrons and wayside neighbors of the system.

Because of the wide variety of way structures and facilities and because of the availability of several different types of transit cars, it was possible to make noise measurements demonstrating those facility and equipment design features or characteristics which lead to reduced or minimized noise production. The noise measurement program was devised, therefore, to evaluate the characteristics of each of the basic types of CTA way structures, using each of the types of transit cars, and to provide for evaluation and determination of the design features or combinations of design features which give the lowest noise. The measurement program was also devised to lead to the development of information leading to the identification of those system or equipment modifications which could give a significant reduction of the noise exposure for CTA patrons and possibly for reduction of noise transmitted to wayside areas. The main concentration of the study was to be on the reduction of in-car noise for all types of operations and the reduction of subway station platform noise levels with some study of the possibilities for reduction of the noise from elevated structure operations.

To accomplish the goals of the study, the program included measurements of [1] car equipment noise levels with the cars raised on jacks permitting the propulsion systems and wheels to spin freely, [2] car interior noise levels with the cars operating on various configurations of elevated structure, ballast and tie track, and subway installations, [3] wayside noise levels for operations on elevated structure, on ballast and tie track with worn continuous rail, smoothed continuous rail, and jointed rail, [4] wayside noise levels in subways with concrete trackbed and ballast and tie track, and [5] subway platform noise levels in subways with concrete trackbed and ballast and tie track. In each case, except for the subway wayside and platform noise levels, the measurements were accomplished using special trains so that specific and well defined operating conditions could be used for making the measurements. This is necessary in order to provide for valid comparisons of performance characteristics.

For each of the test sets, 2-car trains with cars from the 2000 series, the 2200 series, and the 6000 series were used. Measurements were made at the same or comparable test conditions as far as possible using the same train from each car series. Each pair of cars selected for the tests was a typical good condition train chosen to be representative of the series, except for two pairs of modified 2000 series cars included for evaluation of the effects of the modifications. For some of the measurements, substitute standard cars were used, however, most of the tests were accomplished with the same pairs of cars. For the subway wayside and station platform noise levels it was necessary to make measurements using revenue trains, therefore the test conditions were less well defined but the measurements gave numbers characteristic and typical of the noise exposure for patrons.

Most of the noise data was obtained using the special trains operating on Saturday and Sunday on sections of track not used for regular operation on weekends and available for special train test runs. The tests, therefore, were not run on all sections of the CTA way structures, but rather were run on representative sections of each type of track structure. In all cases the trains were run in both directions on the same track or multiple runs for similar conditions were used to obtain averaged performance data.

All of the measurements were accomplished using portable battery operated sound level meters and precision calibrated magnetic tape recorders for recording so that the noise data could be analyzed in detail after completing each measurement series. The data analysis was accomplished by playing back the tape recordings through a real time analyzer with filter set and A-weighting network in order to obtain octave band frequency analyses and A-weighted levels for each of the tests or operating conditions, using identical analysis procedures. The real time analyzer used for the analyses is a device which uses digital techniques for evaluating and calculating the true root-mean-square [rms] values of the noise levels for each event. This method of analysis eliminates the errors inherent in manual reading of meters or strip chart records in the analysis of noise data and assures that the data for each of the types of vehicles were evaluated in exactly the same manner. Since it was expected that noise level differences between some of the vehicles or facility configurations would be small, the analysis procedure was devised to maximize consistency. All differences in the presented results should represent differences in the performance of the vehicles and facilities rather than representing influences of small differences in analysis technique or performance of the readings.

The report includes a discussion of the noise measurement procedure and the facilities used for the measurements, a discussion of the noise measurement results, discussions of the comparisons of vehicle and way structure type performances with evaluation and identification of those design features and characteristics which result in the lowest noise and those modifications or changes in the system facilities which could lead to reduced noise from operations. The report also includes an evaluation indicating further information which is needed, further measurements or experiments which are recommended, and a general evaluation of the potential for reduction of noise from the CTA rail transit operations.

The arrangement of the report is such that the discussions in the body of the report incorporate graphs indicating summarized or average performance in terms of noise levels generated, with the appendices giving detailed noise data for each of the operating conditions and tests which were performed. Appendices A through G indicate the analysis of the averaged wayside and in-car noise levels obtained for each of the tests and each operating condition. It was necessary to make the detailed analysis of each of the sets of data in order to derive the typical or average performance characteristics for the comparisons and evaluation and the graphs of noise data from individual tests are included since they present details which may be of interest or needed in evaluating specific problems or situations which are not discussed in the report. The detailed data charts provide the necessary information for comparisons of performance and evaluations of the noise levels produced. In particular, the octave band analysis charts provide a means for evaluating the effects of different design features or modifications on the different sound frequency ranges. This is important because some differences in the designs or some facility modifications may affect one portion of the frequency range but not have a significant effect on more important ranges or on an overall measurement such as the A-weighted sound level.

II. NOISE MEASUREMENT PROCEDURES

The general procedure used for measuring the noise of the CTA transit trains consisted of making calibrated tape recordings of the noise for each test condition. The tape recordings were then analyzed using laboratory analysis equipment to obtain the noise data using a consistent procedure. In all cases multiple readings were taken either in terms of repeat runs in opposite directions or multiple readings for the same condition. This was done to obtain average results and to minimize the effects of non-typical operating conditions or other anomolous effects which influence individual readings.

Figure 1 indicates block diagrams of the measurement systems used. In each case either a sound level meter or a sound level meter microphone was used as the sensor to observe the sound level with the electrical signal from the microphone being recorded on a precision magnetic recorder. Figure 2 indicates the block diagram of the analysis system used for analyzing the recorded noise data. The analysis system produced two types of output; [1] a strip chart recording indicating the A-weighted sound level of each of the events recorded on the magnetic tape and [2] a sound level and frequency analysis by octave bands and 1/3 octave bands, produced by the real time analyzer and printer. The real time analyzer was used in a manner to produce a true root-mean-square frequency analysis for each event measured. The results from the multiple runs were manually averaged using the individual printed analyses.

Where steady-state conditions could be achieved, such as for measurements of the car equipment noise with the cars on jacks and the wheels spinning or for the measurements of car interior noise, the real time analyzer was used to integrate and average the noise level over a period of 4 to 16 seconds, depending on the length of time for which steady-state conditions were established. For passby events such as the wayside noise for trains operating on elevated structure, ballast and tie tracks or in the subway, the strip chart level recorder was used in conjunction with the real time analyzer. The strip chart recorder was used to determine the time on the recording at which the maximum noise level for each event occurred. The integrating period for the real time analyzer was then manually selected to correspond with a 2 second or 4 second time period during the time of maximum noise level for each passby event. The data presented, therefore, represents either the average of the sound level for a steady event such as car interior noise for constant speed operation or the average of the maximum noise level which occurs during the passby of a transit train.

The cars used for most of the tests were selected to represent typical good condition car pairs from each series tested -

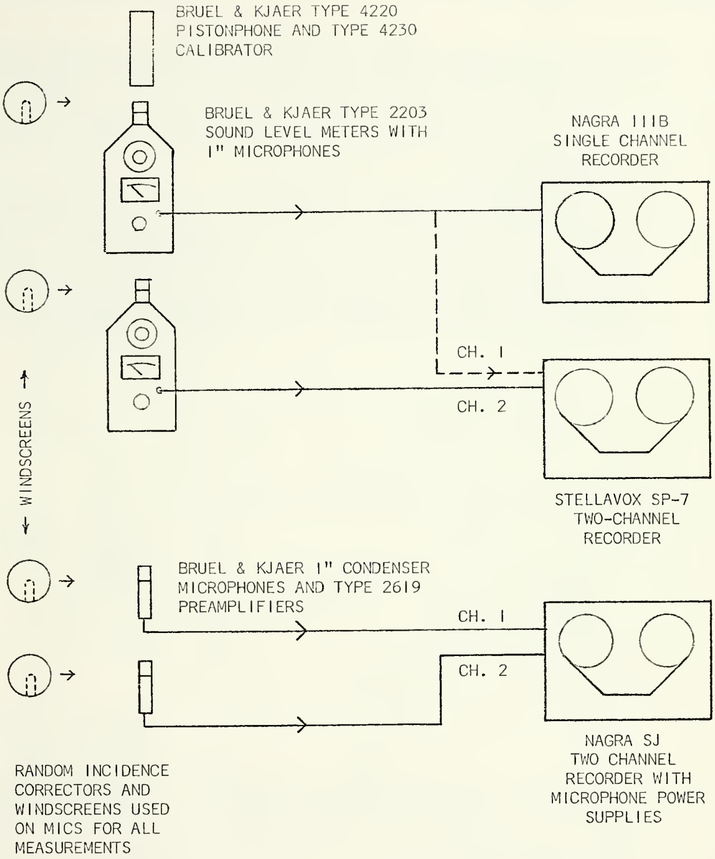


FIGURE 1 BLOCK DIAGRAMS OF THE MEASUREMENT SYSTEMS USED FOR RECORDING THE CTA TRANSIT TRAIN NOISE

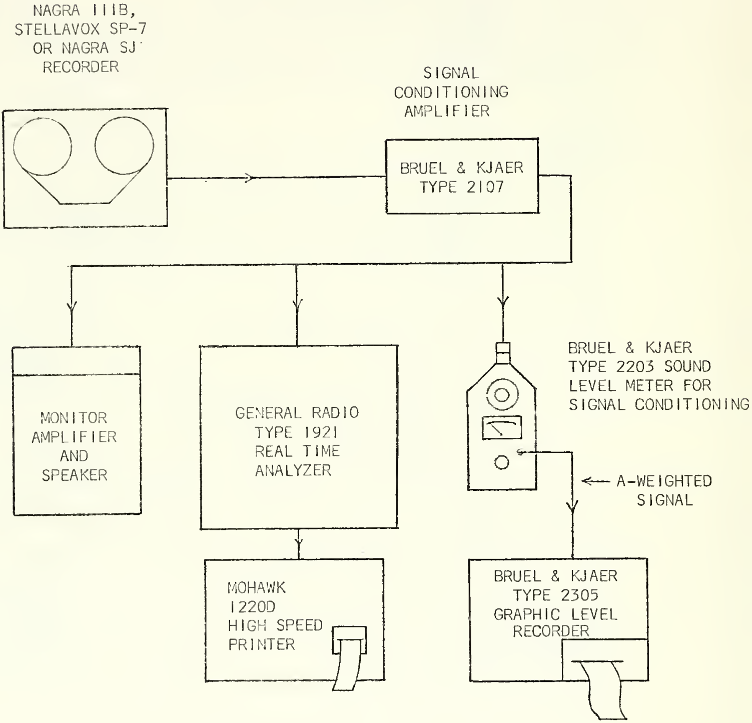


FIGURE 2 BLOCK DIAGRAM OF SYSTEM USED FOR ANALYSIS OF THE RECORDED NOISE DATA

except for the specially modified cars. Table I below indicates the selected transit cars which were used for the noise tests. For all of the measurements involving controlled testing with 2-car trains, an attempt was made to use the same 2-car set for each of the measurements, however, in some instances it was necessary to use a substitute 2-car train for the standard cars.

The trains used for the tests included a typical pair from the 2200 series, cars 2207/2208, a typical pair from the 6000 series with B-3 trucks, cars 6623/6624, and a typical pair from the 2000 series, cars 2059/2060. For some of the tests an additional 6000 series pair with B-2 trucks was used to obtain comparative measurements for the two types of 6000 series trucks and for a number of the measurements some modified 2000 series cars, as listed below, were used.

TABLE I TRANSIT CARS USED FOR CONTROLLED TESTS

Series	Car Number	Status or Conditions
6000	6623/6624	Series Standard - B-3 Trucks
	6391/6392	B-2 Trucks - Newly Overhauled
2200	2207/2208	Series Standard
2000	2059/2060	Series Standard
	2177/2178	Substitute Standard
	2147/2148	Overhauled - Modified Trucks
	2173/2174	Overhauled Trucks with Special Soft Journal Sleeves

Most of the tests reported herein were done with the cars listed in Table I. However, all subway wayside noise and subway station platform noise tests were done with revenue service trains and the data represent typical results for the trains which happened to be in use at the measurement time. Also some controlled tests were done with 4-, 6- and 8-car trains on ballast and tie tracks to obtain data on the effects of train length.

Cars 2147/48 were used to indicate the effect of 2000 series truck overhaul with modifications. Cars 2173/74 were cars with newly overhauled trucks and specially modified journal sleeves giving considerably softer mounting for the axle journals. The specially modified truck journals were installed on cars 2173/74 because of concern relative to truck design for a new series of cars to be purchased by CTA. The original or main purpose of the experimental modification was to test the cars for ground vibration created by operation on elevated structures to determine if the modification of the journals would reduce the transmission of vibration to the support structure and thus alleviate one of the disadvantages found in newer car types which do not incorporate primary springs in the truck design.

For the vibration level experiments on the elevated structure the rubber journal sleeves on the LFM trucks of cars 2173/74 were replaced with softer journals to create the effect of primary springing on a truck of a type which does not incorporate primary springs. The standard journals have a stiffness of 500,000 lbs/in and these were replaced with journals having a spring rate per journal of 17,500 lbs/in, a reduction in stiffness of 30 to 1.

Operation of the cars with the softer journals indicated a subjective or apparent reduction of the noise in the car interior and there was noticeable decrease in the vibration level in the cars. Thus, there was a considerable improvement in the ride quality as observed by comparison with other unmodified cars. Because of these results it was decided to include these cars in the noise measurement test series to objectively determine the effectiveness of the soft journal springs on both car interior noise and wayside noise.

The following paragraphs indicate the specific procedures used for each of the types of measurements included in the test series:

A. Car Equipment Wayside Noise

The car equipment wayside noise tests were performed at the Harlem Shop. The objective of the tests was to determine the wayside noise produced by the propulsion equipment and auxiliary equipment as a separate component of the total noise without the influence of wheel and rail noise which accompanies normal operation of the transit cars. With data on the equipment noise it is possible to make some determinations of the principal components of the total noise radiated during the vehicle operations.

Ideally equipment noise tests should be performed outdoors on ballast and tie track. However, it was not possible to do this and because of the convenient jacking arrangement available in the Harlem Shop, the measurements of the propulsion system wayside noise with the cars on jacks and the wheels spinning were performed in the shop building. Some supplementary tests were performed to provide a means for correcting the noise data to compensate for the reflection and reverberation of the sound in the shop building. The reflection and reverberation due to the enclosure, of course, caused the sound level readings to be somewhat higher than would be experienced out-of-doors in a relatively reflection-free environment.

Because of the fact that the measurements of car equipment noise were done primarily inside the shop, the microphones were placed at 15 ft and 25 ft from the car centerline rather than at 25 ft and 50 ft which were used for all of the outdoor measurements for ballast and tie track and elevated structure wayside noise. The measurement arrangement is indicated on Figure 3. Figures 4 and 5 present photographs of the equipment and test setup. For each pair of cars the vehicles were raised up from floor level using the maintenance jacks in the shop. The trucks of one car of the set were supported on blocks under the truck frames and the rail jacks lowered to free the wheels for the spin tests. The car propulsion systems were operated at several speeds and the noise was measured at each speed where reasonable speed stability under the free-wheeling conditions could be obtained. The measurements were at the 15 ft and 25 ft distances from the car centerline at locations opposite each truck and opposite the center of the car. The data presented are the average of the data obtained at the three positions for each distance and for each speed of operation. The noise from the auxiliary equipment was measured at 15 ft and 25 ft from the car centerline opposite the location of the equipment under the car.

To provide a means for correcting the data obtained inside the shop to be more nearly equal to data which would have been obtained with cars on jacks out-of-doors, a supplementary series of measurements was made with two of the car sets located on ballast and tie tracks in the storage yard outside the shop building. Measurements of the auxiliary equipment noise during normal operation were performed at 15 ft and 25 ft from the track centerline for direct comparison with the same measurements made inside the shop building with the same equipment and same cars. This data provides a direct means for compensating the equipment noise data for the influence of reflection and reverberation in the shop building.

B. Ballast and Tie Track Wayside Noise

For the ballast and tie track wayside noise measurements a section of the elevated retained embankment on the Howard Line was designated as the test section. In this area track #4 on the east edge of the embankment included a section of old continuous welded rail and a section of reconstructed or new continuous welded rail which was installed in the summer and

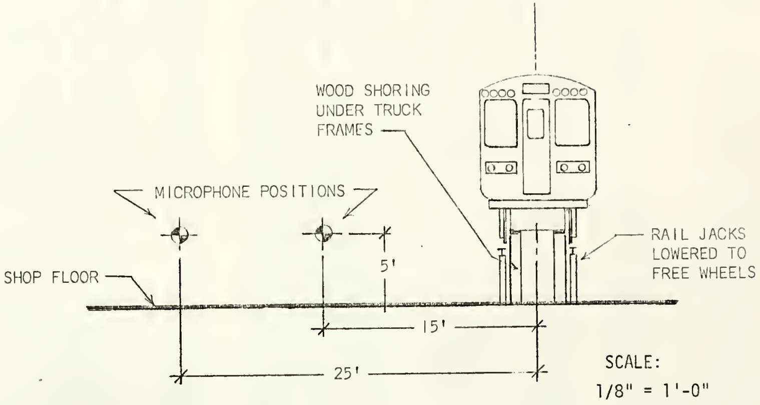
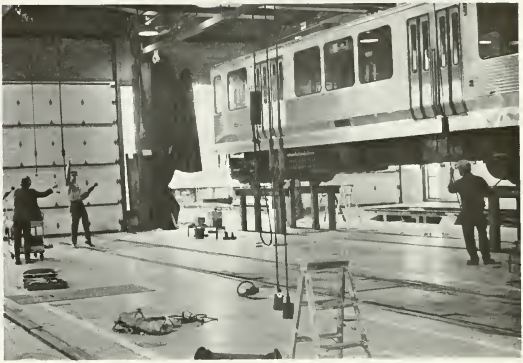
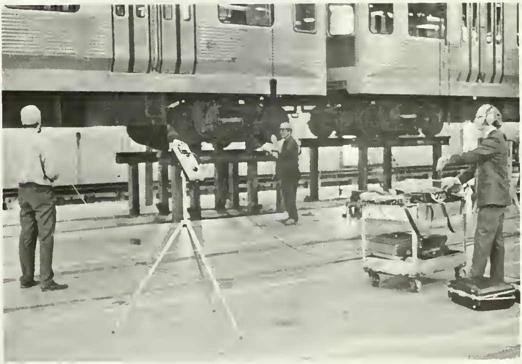

WOOD SHORING UNDER TRUCK FRAMES
MICROPHONE POSITIONS
RAIL JACKS LOWERED TO FREE WHEELS
SHOP FLOOR
5'
15'
25'
SCALE:
1/8" = 1'-0"

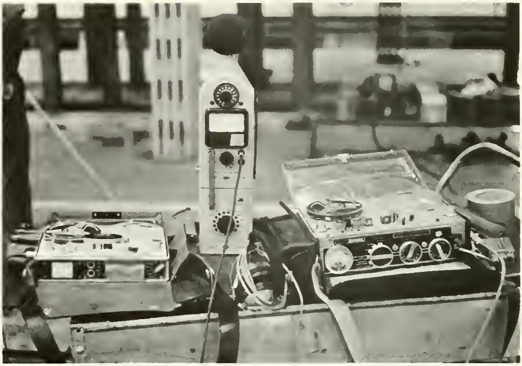
FIGURE 3 TEST ARRANGEMENT USED FOR THE EQUIPMENT NOISE MEASUREMENTS IN THE HARLEM SHOP MAINTENANCE BUILDING





VIEW SHOWING SOUND LEVEL METER MICROPHONE AT AXLE HEIGHT AND CARS ON JACKS WITH TEST IN PROGRESS

FIGURE 4 OVERALL VIEWS OF THE TEST ARRANGEMENT WITH THE TRANSIT CARS ON JACKS FOR MEASURING EQUIPMENT NOISE LEVELS



TAPE RECORDER AND SOUND LEVEL METER

SOUND LEVEL METER SET UP AT AXLE HEIGHT FOR MEASURING PROPULSION SYSTEM NOISE WITH THE WHEELS SPINNING

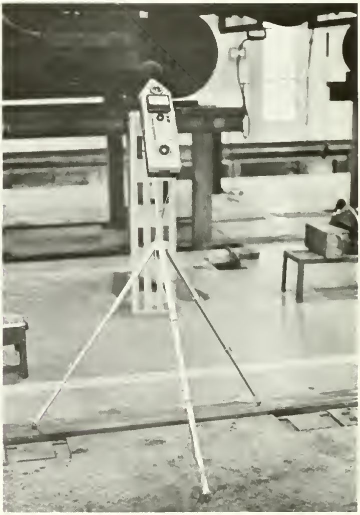


FIGURE 5 PHOTOGRAPHS OF MEASUREMENT AND RECORDING EQUIPMENT SET UP IN THE HARLEM SHOP BUILDING

and fall of 1972 just prior to the measurements. Track #1 on the west side of the embankment was jointed rail. Thus, the selection of this location provided a test area where tests could be performed with worn or old continuous welded rail and new continuous welded rail, both before and after grinding, and on jointed rail for ballast and tie track.

The width of the embankment and the location of the tracks used for testing were appropriate to provide the ability to make measurements at 25 ft and 50 ft from track centerline. The test arrangement is shown on Figure 6 and Figure 7 presents some photographs of the area showing the microphones in place at two of the test locations along this section. The test sites used were selected from those locations available at each of the types of track configuration where the maximum train speeds could be achieved with sufficient buffer distance to stop the trains and also where buildings along the wayside were sufficiently removed to avoid reflections which could influence the measurements at the 50 ft position. The microphone at the 25 ft position was actually set at about 24 ft from the test track centerline in order to avoid interference with revenue trains moving on track #2, one of the center tracks.

The two sites selected for the measurements were a few hundred feet south of the Bryn Mawr Station for the tests on old continuous welded rail and jointed rail and a few hundred feet north of the Bryn Mawr Station for the new continuous welded rail.

The procedure used for all of the wayside noise tests with the various trains operating on the old or worn continuous rail with corrugations, the new continuous rail before grinding, the new continuous welded rail after grinding and the jointed rail was to operate the special 2-car test trains at controlled speeds in 10 mph increments recording one passby in each direction for each speed. This provided at least two data points for each speed with each type of car. The speeds used generally included 30, 40 and 50 mph, or 47 mph for those cars which could not reach 50 mph in the test area or which have maximum speeds of 45-47 mph. In some cases, where time permitted, data was also taken at 10 and 20 mph and where there was sufficient room and speed capability some data was obtained at 60 and 70 mph. For most of the data there was little interference from background noise due to street traffic or airplane overflight, although for 10 mph operation in many cases the background noise made it difficult to obtain good recordings and at 20 mph in some cases the recordings were affected by background noise. During one series of tests, some measurements with long trains - 2-, 4- and 8-car trains - were performed using the 2000 series test trains, and an extra pair, coupled together.

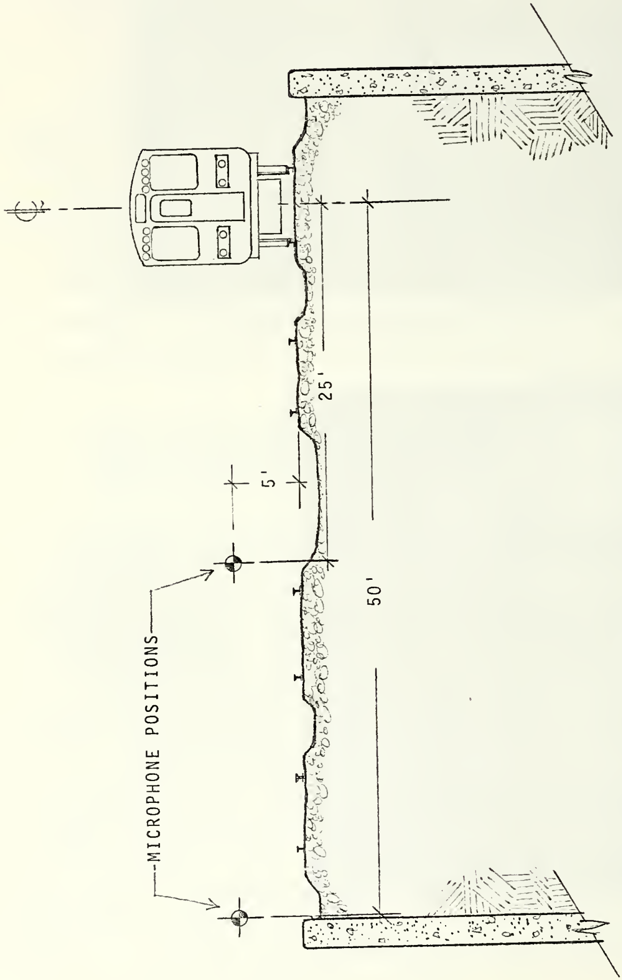
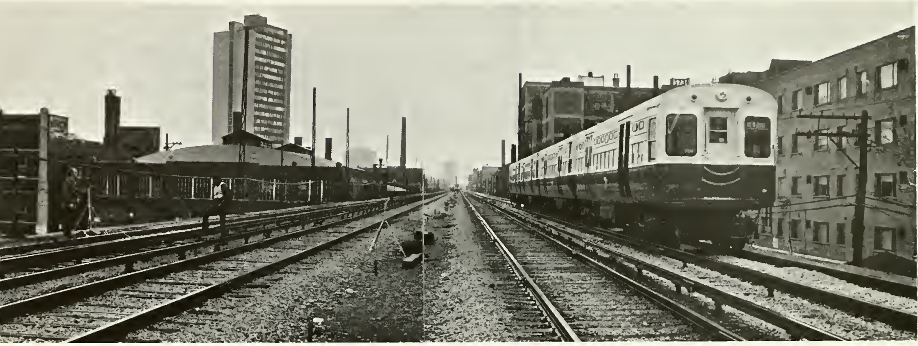
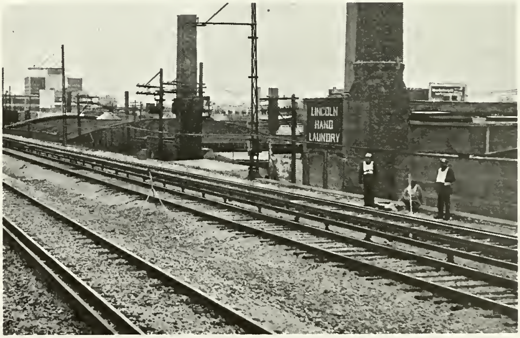


FIGURE 6 TEST ARRANGEMENT USED FOR THE BALLAST & TIE TRACK WAYSIDE NOISE MEASUREMENTS AT THE TEST TRACK SECTION ON THE HOWARD LINE



OVERALL VIEW OF THE TEST TRACK AREA LOOKING SOUTH, SHOWING THE MICROPHONES AT 25 FT AND 50 FT AND A TEST TRAIN ON THE JOINTED RAIL TEST SECTION, TRACK #1



VIEW SHOWING THE MICROPHONES AT THE TEST SITE
FOR WORN CONTINUOUS WELDED RAIL TESTS ON TRACK #4

FIGURE 7 PHOTOGRAPHS OF THE TEST SET UP AND FACILITIES FOR THE BALLAST AND TIE TRACK WAYSIDE NOISE TESTS

C. Elevated Structure Wayside Noise

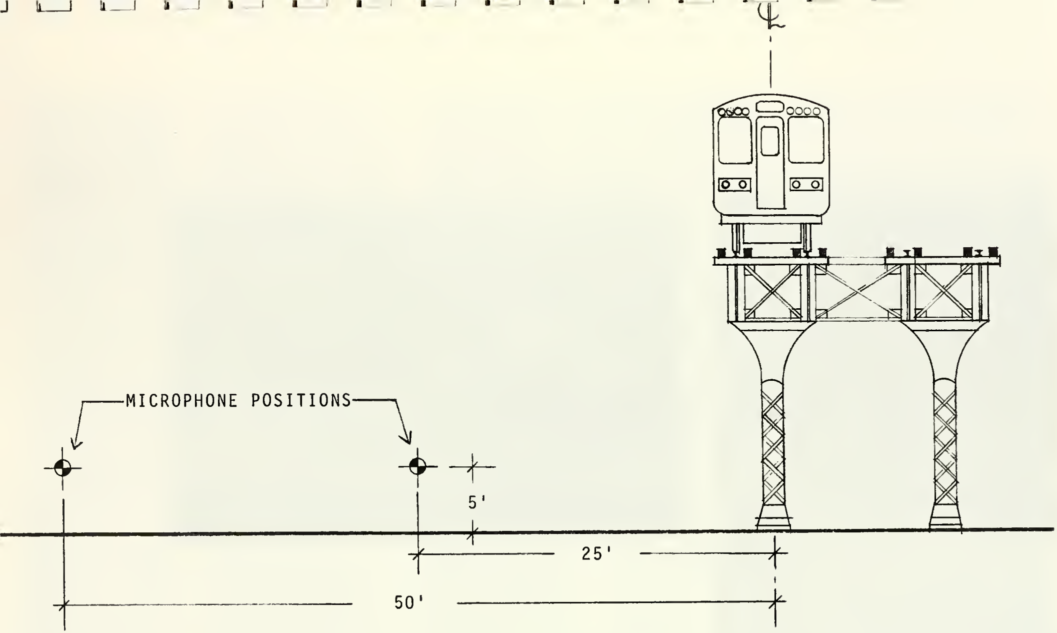
The measurements of wayside noise at elevated structures were obtained using a procedure similar to that for the ballast and tie wayside noise measurements. The test arrangement is shown on Figure 8. The tests were performed with the microphones located at about 4-1/2 ft above the ground and at positions 25 ft and 50 ft from the centerline of the track on which the trains were operating on the elevated structure. The open web structure measurements were made at a location along the Ravenswood Line where the elevated is a 2-track structure, between the Merchandise Mart and Chicago Avenue Stations. The measurements with solid web structure were made at a location where the structure is 4-track between the Chicago Avenue and Sedgwick Stations on the Ravenswood Line. On the 4-track structure the trains were operated on track #3, the center track nearest the side of the measurement. In both cases the ground beneath the structure and to the wayside was reflective consisting either of roadways and a vacant lot or bare, hard ground and asphalt school yard.

The test procedure, as with the ballast and tie tests, was to run each of the test car pairs by the microphone location at constant speeds in increments of 10 mph to obtain noise level recordings of the train passby noise for a series of clearly defined conditions. For each speed the trains were operated at least once in each direction giving at least two data points for each speed and each car type.

D. Subway Structure Wayside Noise

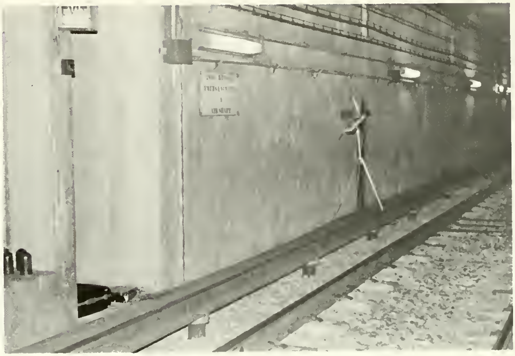
To obtain data on the wayside noise in subways, i.e., a measure of the reverberant sound level outside the cars when operating in the subways, measurements were made on the walkway at three locations in the subway structures. The measurements consisted of recording the noise due to passbys of revenue trains at each of the test sites. Data were obtained, therefore, for a variety of lengths of trains and types of cars, speeds were estimated and obtained by timing with a stopwatch. Figure 9 presents photographs indicating the details of the test setup in the subways.

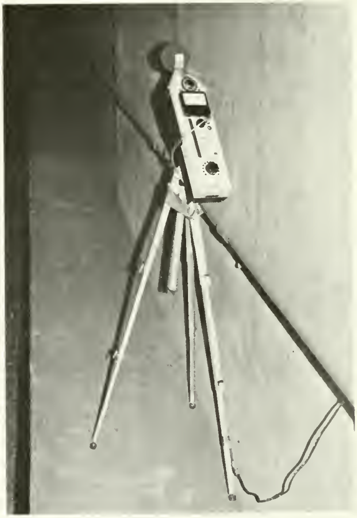
The test sites, which were located along the Congress and Milwaukee Lines, included tunnel with concrete trackbed, tunnel with ballast and tie track and box section with ballast and tie track. For the tunnel with ballast and tie track the location was just east of Clinton Station, a horseshoe tunnel. For the tunnel with concrete roadbed the location was just north of Chicago Station, also a horseshoe tunnel section. The box section tests were done near the Dawson Emergency Exit north of Logan Square Station.



SCALE:
1/8" = 1'-0"

FIGURE 8 TEST ARRANGEMENT USED FOR THE ELEVATED STRUCTURE WAYSIDE NOISE MEASUREMENTS ON THE RAVENSWOOD LINE





TWO VIEWS OF THE
SOUND LEVEL METER
SET UP ON THE
SUBWAY WALKWAY

FIGURE 9 PHOTOGRAPHS SHOWING THE EQUIPMENT SET UP FOR MEASURING SUBWAY WAYSIDE NOISE

E. Subway Station Platform Noise

Noise measurements on subway station platforms were made by setting up the sound level meter microphone at 4-1/2 to 5 ft height, approximately standing head height, and 5 ft from the edge of the platform in locations on the platforms selected as appropriate to give representative noise data. Figure 10 presents a photograph of the noise measurement setup on a station platform. The measurements obtained on the subway station platforms included observation of the noise levels created by trains passing through and by trains which stopped at the station location. In the latter case both the noise of the approaching and departing trains were recorded and analyzed.

The platform noise measurements included observations in the long platform tunnel stations, both the Dearborn and State Street subway platforms. Also measurements were done in a short tunnel station with concrete trackbed, the Chicago Station; a tunnel station with ballast and tie trackbed, the Clinton Station; and a box section subway station with ballast and tie trackbed, the Belmont Station, all on the Congress and Milwaukee Lines. At the Belmont Station data was taken both in the low ceiling and the high ceiling portions of the platform space.

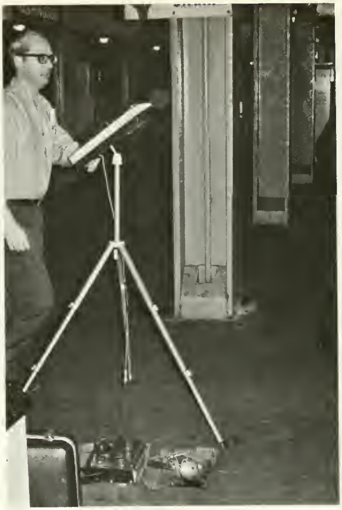
All of the train operation noise level data on the station platforms was obtained for revenue trains passing through or stopping in the stations and thus the data were for a variety of car types and lengths of train for the speeds characteristic of operations in and out and through the stations. The data thus represents typical noise levels experienced by patrons on the station platforms.

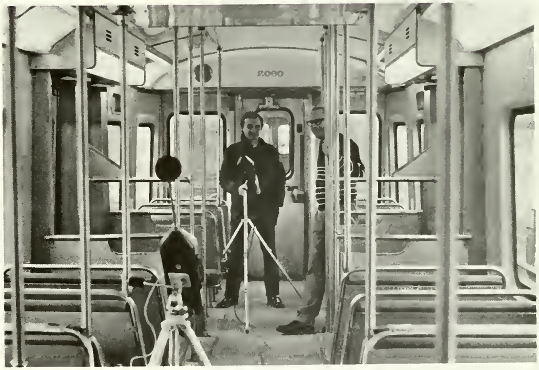
F. Car Interior Noise

For the car interior noise measurements two positions along the centerline of the car were used for all of the measurements; one at the center of the test car of the pair and one directly over the #2 truck near the center of the 2-car train. The microphones were set at about 4-1/2 ft height, the average between seated and standing head height. Figure 10 presents a photograph showing the sound level meters and microphones in place within a transit car.

The measurements were accomplished by running each test train between revenue trains at constant operational speeds for each of the different characteristic sections of track between stations, such as different types of elevated structure, subway and at-grade tracks. For cars 2207/08 the interior noise measurements were made for complete circuits of the Lake Line, a partial circuit of the Ravenswood and Howard Lines with repeat runs in opposite direction, followed

SOUND LEVEL METER
ON STATE STREET
SUBWAY PLATFORM





2000 SERIES CAR INTERIOR

FIGURE 10 PHOTOGRAPHS SHOWING SOUND LEVEL METER PLACED ON STATION PLATFORM AND CAR INTERIOR

by a circuit consisting of part of the Congress Line and the complete Milwaukee Line. For the 2000 series test trains the the interior measurements were made with the trains operating on complete circuits of the Congress and Milwaukee Lines. The 6000 series trains, 6623/24 with B-3 trucks and 6391/92 with B-2 trucks were tested by operating along a circuit made up of parts of the Howard and the Jackson Park/Englewood Lines.

In completing the car interior noise measurement the test procedure was to record the noise levels in the cars as the trains proceeded at constant speed over each of the characteristic track sections, using one set of operating speeds in one direction on the line and a second set of speeds on the return trip. Where it was possible, due to repetitive types of structures being available on the line, or where the length of track section was sufficient to change speeds, other speeds were included. In general, data were obtained at 30, 40 and 50 mph, or at 47-48 mph for those trains with maximum speed of about 47 mph. Some runs at higher speeds were made on long sections of elevated structure on the Lake service line and on the ballast and tie track test section on the Howard Line.

Average data were obtained by taking long-time averages of the car interior noise for operation at constant speed, as described previously in the measurement procedures discussion. In most cases it was not possible to obtain average results for the trains operating in both directions at the same speed for the same section of way structure. The average data reported is the average of the noise level measured over the #2 truck and in the center of the car. Some individual sets of data are included in Appendix E which show the difference in the level at the center of the car compared with the location directly over the truck. The data indicate very consistent and reproducible results, i.e., for similar type track in different locations the noise level was the same, so that the lack of data for both directions, for averaging, does not significantly affect the overall results.

G. Schedule of Noise Measurements

The schedule of noise measurements is indicated in Table II. This table is included to indicate the specific dates for each type or category of measurement which was performed.

TABLE II SCHEDULE OF NOISE MEASUREMENT TESTS

Date	Cars Used	Type of Test
May 13, 1972	2059/60, 2207/08 6623/24	Car Equipment Noise - Cars on Jacks
May 14, 1972	2207/08	Car Interior Noise
May 15, 1972	Revenue Trains	Subway Wayside and Station Platform Noise
June 1, 1972	Revenue Trains	Subway Wayside and Station Platform Noise
June 2, 1972	Revenue Trains	Subway Wayside and Station Platform Noise
Nov. 4, 1972	2059/60, 2147/48 2173/74	Car Interior Noise
Nov. 5, 1972	2207/08, 2059/60 2147/48, 2173/74	Wayside Noise - Open Web and Solid Web Elevated Structures
Nov. 18, 1972	2207/08, 2177/78 2147/48, 2173/74	Wayside Noise - Ballast & Tie Track
Nov. 19, 1972	6623/24, 6391/92	Wayside Noise - Ballast & Tie Track
Nov. 25, 1975	2207/08, 2147/48 2173/74, 6623/24, 6391/92	Wayside Noise - Ballast & Tie Track
Nov. 26, 1972	6623/24, 6391/92	Car Interior Noise

III. NOISE MEASUREMENT RESULTS

The detailed graphs showing the results of the measurements for each of the measurement configurations and train operating speeds are given in Appendices A through G. The charts in the Appendices present the octave band analysis, the overall sound pressure level and the A-weighted sound level for the average result of each measurement. For controlled speed passby noise tests the charts show the average for the trains passing by in both directions, for car interior noise the data are the average of the noise level at the center of car and at the #2 truck, for subway station platform noise and tunnel noise the data are the average for several passbys of transit trains of each type and for the car equipment noise with the cars stationary or on jacks the levels are the average over several seconds of operation at constant conditions. For the car interior noise a few graphs are included to show the individual sound level measurements at the center of the car and at the truck to indicate the difference or relative magnitudes of the sound level in the quietest and noisiest parts of the transit car.

This section of the report presents graphs, tables and discussions showing the overall characteristics of the noise data obtained and summarizing the results of the measurements.

A. Car Equipment Wayside Noise

The measurements of the car equipment wayside noise provide basic data on the sound levels produced by the transit car propulsion systems and auxiliary equipment. These data provide a basis for determining the degree to which equipment noise affects or contributes to the wayside noise for operation of the transit trains on the various way structures. The measurements included both the evaluation of the propulsion system noise with the cars on jacks and the wheels spinning freely and the evaluation of the noise from each of the auxiliary equipment items under the cars and which generate wayside noise during normal operation.

Because the major portion of the noise generated by transit car propulsion systems is the noise generated by the drive motors, measurement of the propulsion equipment noise with the cars on jacks provides a valid measure of the propulsion equipment noise. During normal operations with the motors and gears loaded there may be some additional contribution to the total noise due to gearbox noise, however, in most cases it has been found that the gearbox noise is less than, or at most comparable to, the noise from the propulsion motors. The motors themselves make the same noise whether loaded or unloaded because the predominant source of the noise is the turbulent airflow noise caused by the cooling air flow and normal motor windage noise. This noise is independent of load on the motor. The wayside noise observations did not show that the CTA car equipment produces significant gear noise and it is believed that the measurements with the wheels spinning freely represent a good indication of the propulsion equipment wayside noise with the cars operating under normal conditions.

Table III indicates the measured results obtained with the cars on jacks in the shop building for propulsion system noise for the three types of cars included in the tests. The data are the average for the measurements opposite #1 truck, #2 truck and the car center. Table IV presents similar data for the auxiliary equipment as measured opposite the equipment location under the cars. For comparison, Table V presents wayside noise data for the auxiliary equipment as measured outside the shop building on the ballast and tie tracks in the yard.

TABLE III CTA TRANSIT CAR PROPULSION SYSTEM WAYSIDE NOISE MEASURED IN SHOP WITH CARS ON JACKS AND WHEELS SPINNING

		Distance from Car Centerline	
Car	Speed	15 Ft	25 Ft
2207	35 mph	90 dBA	89 dBA
	50	96	94
2060	35 mph	90 dBA	89 dBA
	46	96	95
	70	105	104
6624	30 mph	84 dBA	82 dBA
	50	94	92

TABLE IV CTA TRANSIT CAR AUXILIARY EQUIPMENT WAYSIDE NOISE MEASURED IN THE SHOP WITH THE CARS ON JACKS

		Distance from Car Centerline	
Car	Equipment Items	15 Ft	25 Ft
2207	Air Conditioner	81 dBA	78 dBA
	Converter	68	65
2060	Air Conditioning System	74	72
2059	Air Conditioning System	79	77
	Converter	60	59
	Inverter	63	61
6624	Motor Generator	74	72

TABLE V CTA TRANSIT CAR AUXILIARY EQUIPMENT NOISE MEASURED OUTDOORS ON BALLAST AND TIE TRACK

		Distance from Car Centerline	
Car	Equipment Items	15 Ft	25 Ft
2207	Air Conditioner	77 dBA	72 dBA
2059	Air Conditioner	75 dBA	70 dBA
2060	Air Conditioner	72 dBA	67 dBA
6624	Motor Generator	69 dBA	64 dBA

The general results obtained from comparison of the measurements in the shop building and those outdoors in the yard are that the levels average about 4 dBA higher at 15 ft and 6 dBA higher at 25 ft due to the reflected and reverberant noise in the shop building.

In order to make the best comparisons between the propulsion equipment noise and the wayside noise for the trains operating on ballast and tie track or elevated structure, the measurements of the propulsion system noise in the shop have been converted to equivalent levels operating out-of-doors at distances of 25 ft and 50 ft from the track centerline. The measurements of car equipment noise made outside the shop on ballast and tie track for the same conditions as for the measurements inside the shop were used to derive the appropriate corrections for the reverberation and reflection in the shop. Further, the 2-car train passby data obtained at 25 ft and 50 ft were compared and the differences averaged to derive the correction from 25 ft to 50 ft for the propulsion system noise. Figure 11 indicates the propulsion system noise for the three types of cars as a function of train speed, normalized to a distance of 50 ft from track centerline for a 2-car train.

The charts on Figure 11 provide an indication of the level of the equipment noise as a component of the total wayside noise of the transit trains. Included on the legend is a mathematical expression of the best fit straight line which corresponds with the data, giving the slope and intercept of the graph. This provides a convenient means for expressing the speed dependence and level of the wayside noise. The expression is given to the right of each car identification number on the chart.

As the data on Figure 11 show, the noise is approximately proportional to the fifth power of the train speed or the rpm of the motors, i.e., proportional to $V^{4.4} - V^{4.8}$, as is expected for windage and cooling air turbulent noise. It is typical of electric motors and the associated cooling fans or cooling airflow to produce noise approximately proportional to the fifth power of the rpm or speed of the motors. Comparison of the noise levels indicated on this chart with later charts in the report, indicating wayside noise for normal train operations, shows that the propulsion system noise is lower than the total wayside noise for operation on elevated structure or ballast and tie track for most operating conditions. Only with recently smoothed continuous welded rail on ballast and tie track is the propulsion system noise of a level which could contribute significantly to the total wayside noise and then only for the highest operational speeds.

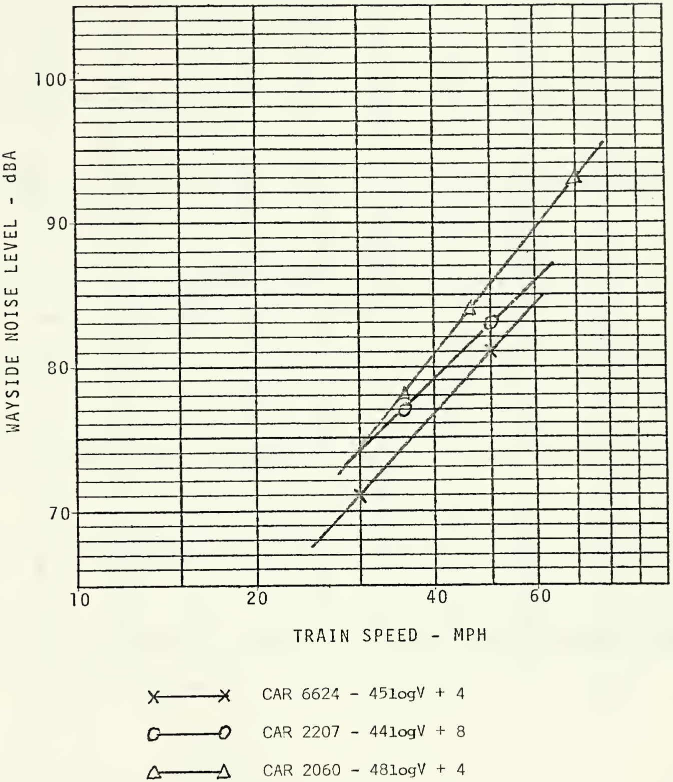


FIGURE 11 PROPULSION EQUIPMENT WAYSIDE NOISE WITH WHEELS SPINNING - DATA NORMALIZED TO 50 FT FROM TRACK CENTERLINE ON BALLAST AND TIE TRACK

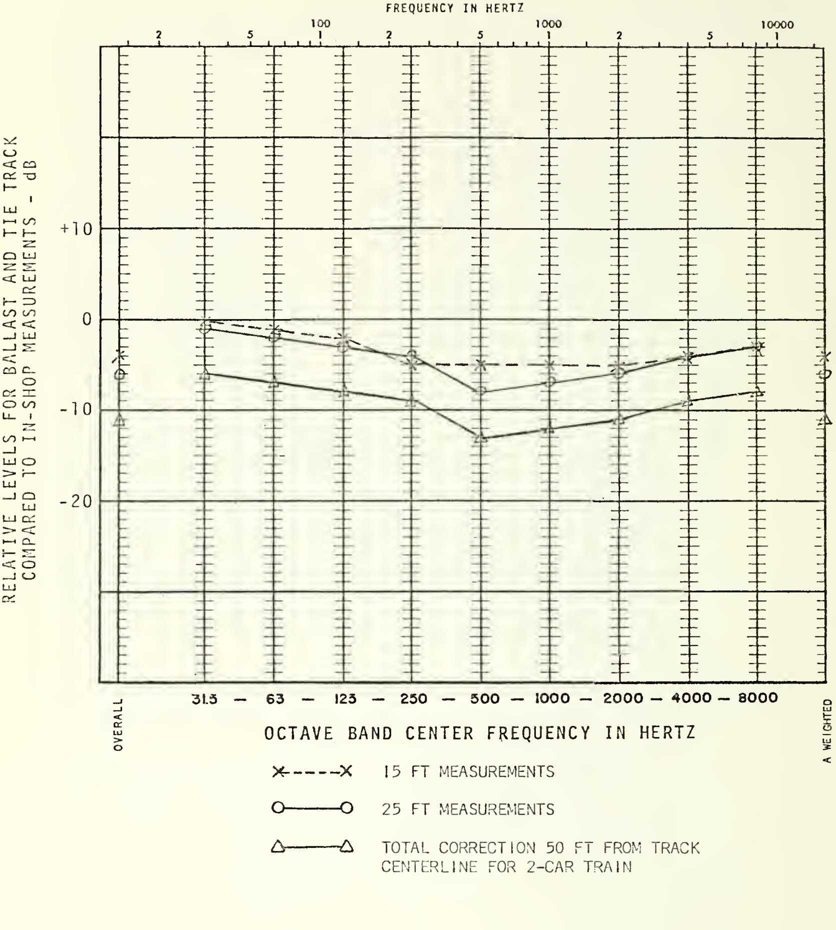


FIGURE 12 AVERAGED CORRECTION FACTORS FOR CONVERTING EQUIPMENT NOISE MEASUREMENTS IN THE SHOP BUILDING TO LEVELS FOR TRAINS ON BALLAST AND TIE TRACK

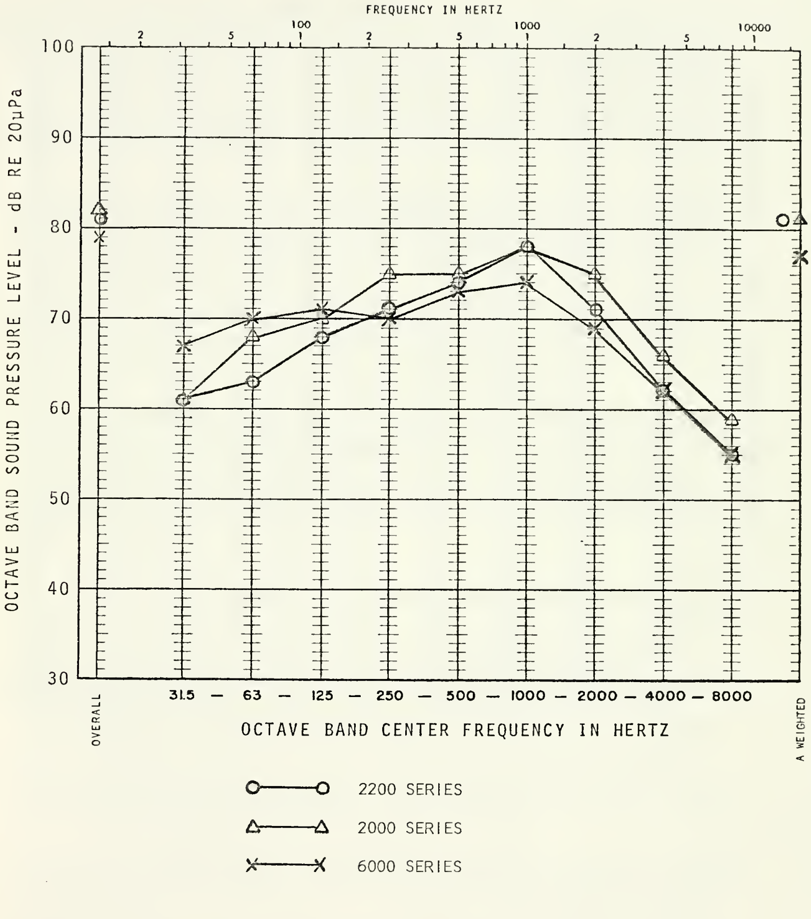


FIGURE 13 PROPULSION EQUIPMENT WAYSIDE NOISE NORMALIZED TO 50 FT FROM TRACK CENTERLINE FOR 40 MPH OPERATION ON BALLAST AND TIE TRACK

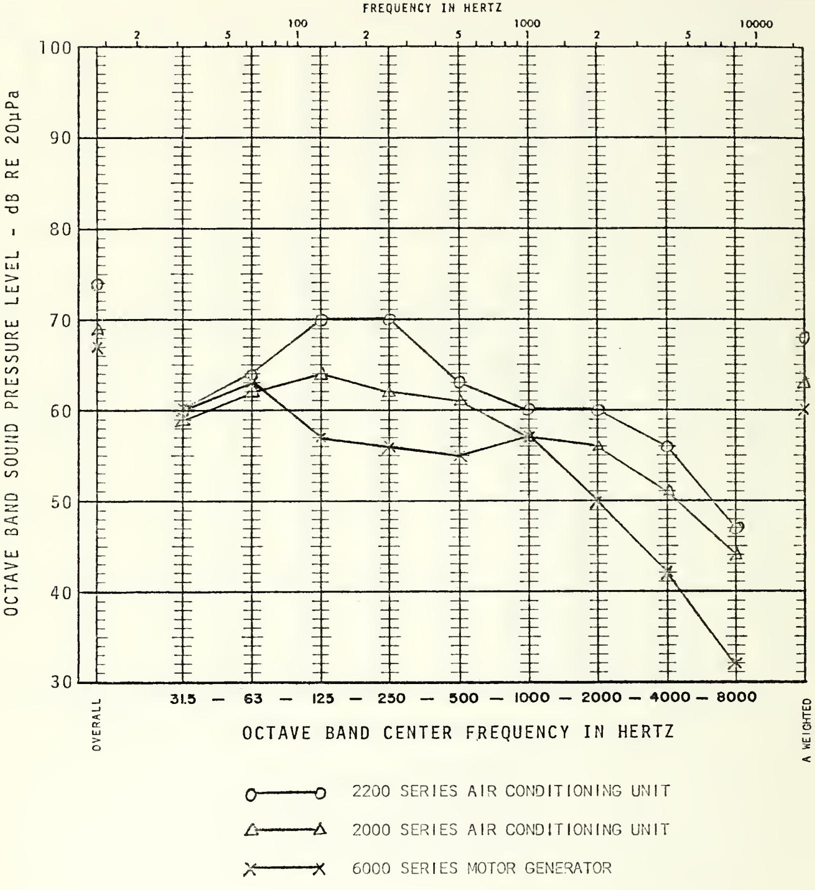


FIGURE 14 TYPICAL AUXILIARY EQUIPMENT WAYSIDE NOISE AT 50 FT FOR BALLAST AND TIE TRACK

Figure 12 indicates the correction factors which were derived from the noise data in the shop building and on ballast and tie track outside the shop coupled with the differences in passby levels at 25 ft and 50 ft. These correction factors were used to determine the adjustments to be applied to the propulsion system noise as measured in the shop to give data corresponding to the values which would have been obtained had it been possible to measure the propulsion system noise on ballast and tie track outdoors.

Figure 13 indicates the typical propulsion equipment noise spectra corrected to the 50 ft wayside position for the 2000, 2200 and 6000 series cars. The purpose of this chart is to provide data for comparison with the wayside passby noise data presented in later sections. The chart shows the average result for approximately 40 mph operation of the transit cars. The spectra do not differ greatly over the range from 30 to 50 mph and the results on Figure 13 can be used for that speed range with the levels adjusted up for speeds higher than 40 mph and down for lower speeds, as indicated by the charts of Figure 11.

Figure 14 presents data on the auxiliary equipment noise for comparison with the propulsion equipment noise and wayside passby noise. It is apparent from the charts on Figure 14 that even the noisiest auxiliary equipment items, the air conditioning systems, do not make sufficient noise to contribute significantly to the wayside noise when the trains are moving on the tracks.

B. Ballast and Tie Track Wayside Noise

The wayside noise for the three series of standard cars and the modified 2000 series cars were measured for a variety of rail conditions. These included jointed rail, old continuous welded rail that was worn and had some corrugations, new continuous welded rail before smoothing and continuous welded rail after smoothing with the rail smoother or grinder. The tests which were done for these rail conditions were the most extensive of all of the various test series included in the evaluation and provide the most complete basis for comparison of the performance of the various types of transit cars and the various types of rail.

The charts of wayside noise at 50 ft and 25 ft for the various combinations of transit vehicle, rail type and operating speed are presented in Appendix B. Figures 15 through 18 present summarizing charts showing the wayside sound levels at 50 ft for the five configurations of cars which were measured on each of the various configurations of rail. Figure 19 shows the summarized results for the overhauled and the specially modified 2000 series cars for the various rail conditions. As for the propulsion system noise, each of the summary charts includes a notation giving the speed dependence of the noise, noted to the right of each car identification reference in the legend of the chart. These expressions indicate the best fit straight line which corresponds to the noise data and provide a convenient basis for comparing the noise generation characteristics for the different car and rail configuration combinations.

The charts of noise level vs speed show that for all of the types of cars the speed dependence and the wayside noise level are essentially equivalent when operating on jointed rail, see Figure 15. The speed dependence is approximately proportional to $V^{3.9}$ and the levels are 5 to 10 dB greater than for worn and smooth continuous welded rail. For the worn continuous welded rail with some roughness and corrugation, Figure 16, the speed dependence is proportional to $V^{3.5} - V^{3.6}$ and for the new continuous rail or smoothed continuous rail, Figures 17 and 18, the wayside noise is approximately proportional to the 2.9 power of the train speed. All of these charts, except for Figures 18 and 19 with data for smooth continuous welded rail, show noise levels considerably greater than for the propulsion equipment as indicated by Figure 11. This indicates that the wayside noise observed is predominantly wheel and rail noise.

There is little difference in performance for the different car types and configurations with the jointed rail or with the worn, corrugated continuous welded rail. However, when the rail is in good condition and smooth there is considerable difference in the results for wayside noise, depending on type and configuration of car. In particular, the modified 2000 series cars with the soft journal sleeves resulted in considerably lower noise level on the continuous welded rail and probably the noise from that train had substantial contribution from the propulsion equipment at the highest speeds.

Octave band analyses showing the comparative performance of the five car configurations on the ballast and tie track are given by the graphs in Appendix B. Figures 20, 21 and 22 present averaged results showing comparisons of performance of the same car types on jointed rail and smoothed continuous rail. The charts on Figures 20, 21 and 22 are for 40 mph operation, however, the noise spectra are essentially the same shape for 30 to 50 mph and these charts, therefore, show the comparative performance over that range of operating speeds. For speeds other than 40 mph, the actual levels should be adjusted up for higher speeds and down for lower speeds as shown by the charts on Figures 15 through 18.

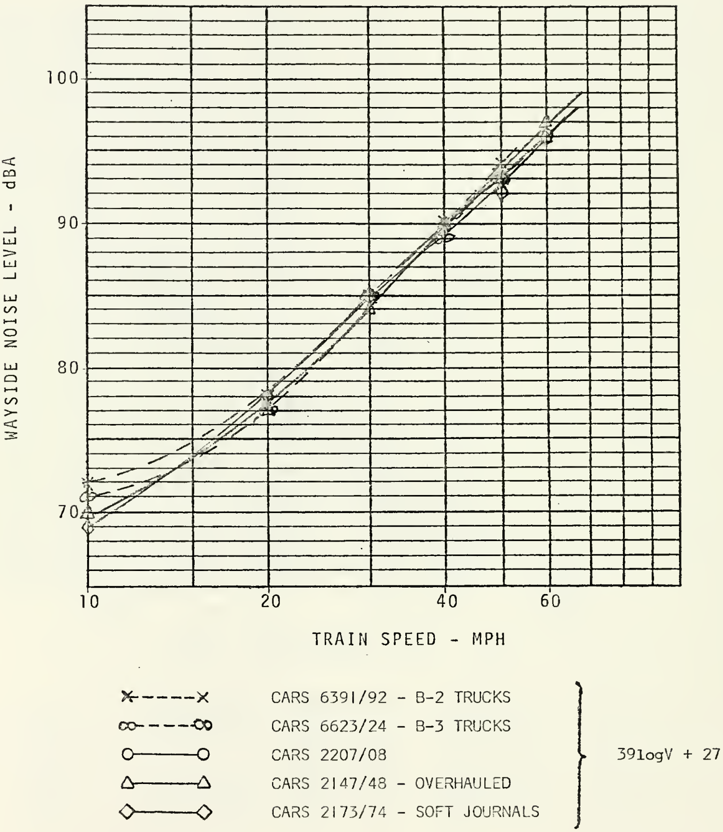


FIGURE 15 WAYSIDE NOISE LEVEL AT 50 FT FOR BALLAST AND TIE TRACK

2-CAR TRAINS - JOINTED RAIL

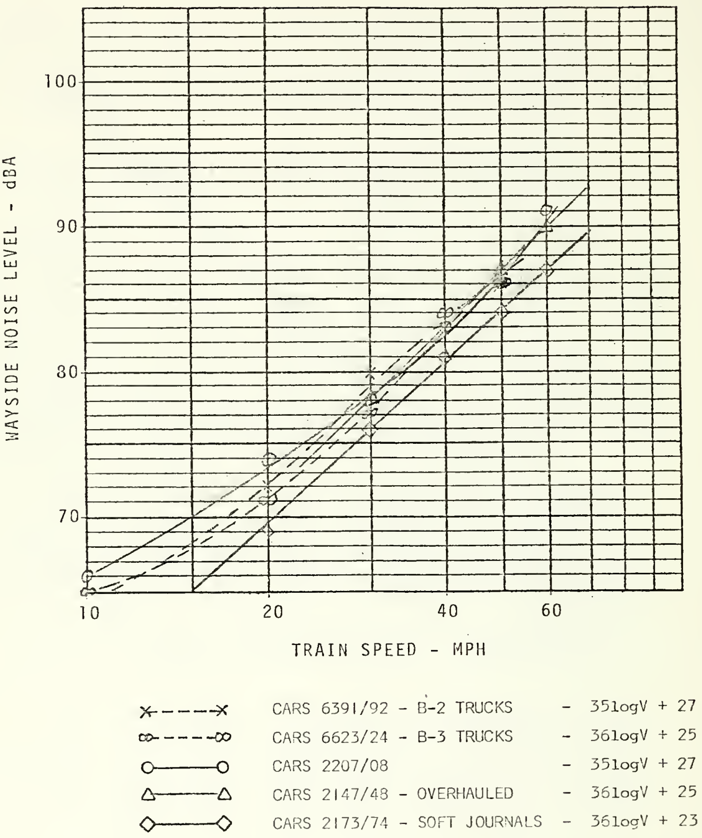


FIGURE 16 WAYSIDE NOISE LEVEL AT 50 FT FOR BALLAST AND TIE TRACK

2-CAR TRAINS - WORN CONTINUOUS WELDED RAIL

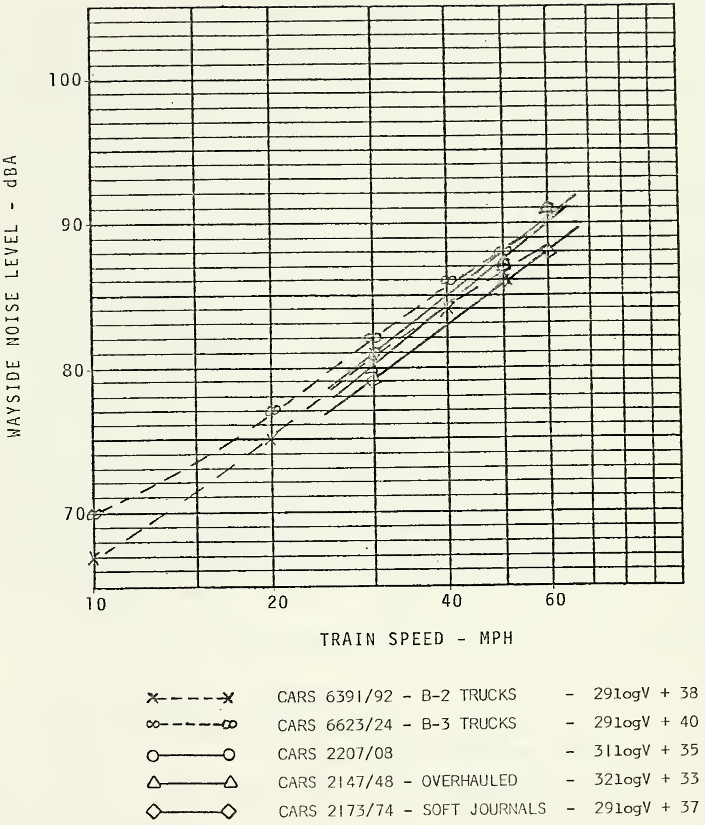


FIGURE 17 WAYSIDE NOISE LEVEL AT 50 FT FOR BALLAST AND TIE TRACK

2-CAR TRAINS - NEW CONTINUOUS WELDED RAIL BEFORE SMOOTHING

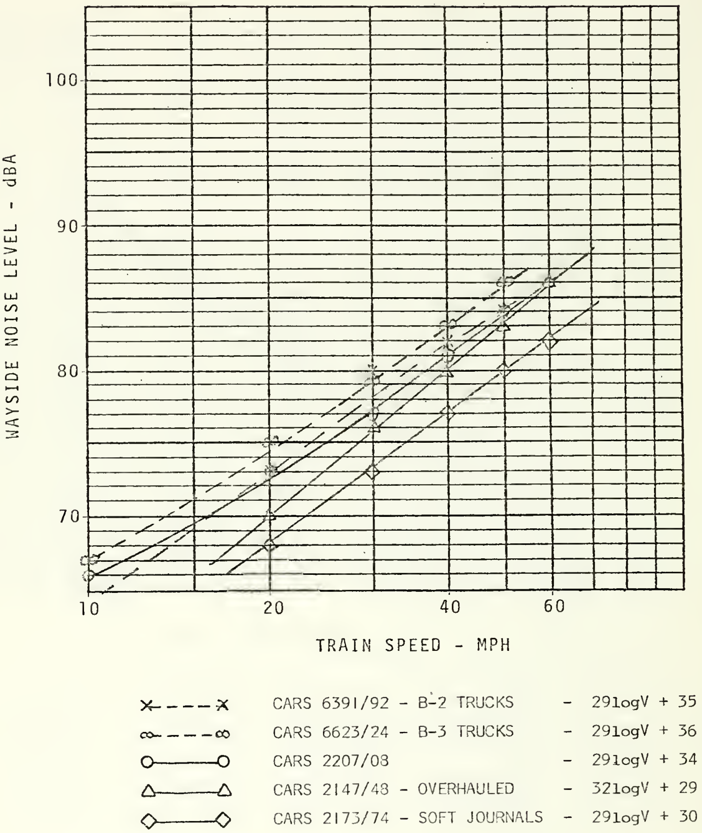


FIGURE 18 WAYSIDE NOISE LEVEL AT 50 FT FOR BALLAST AND TIE TRACK
2-CAR TRAINS - SMOOTHED CONTINUOUS WELDED RAIL

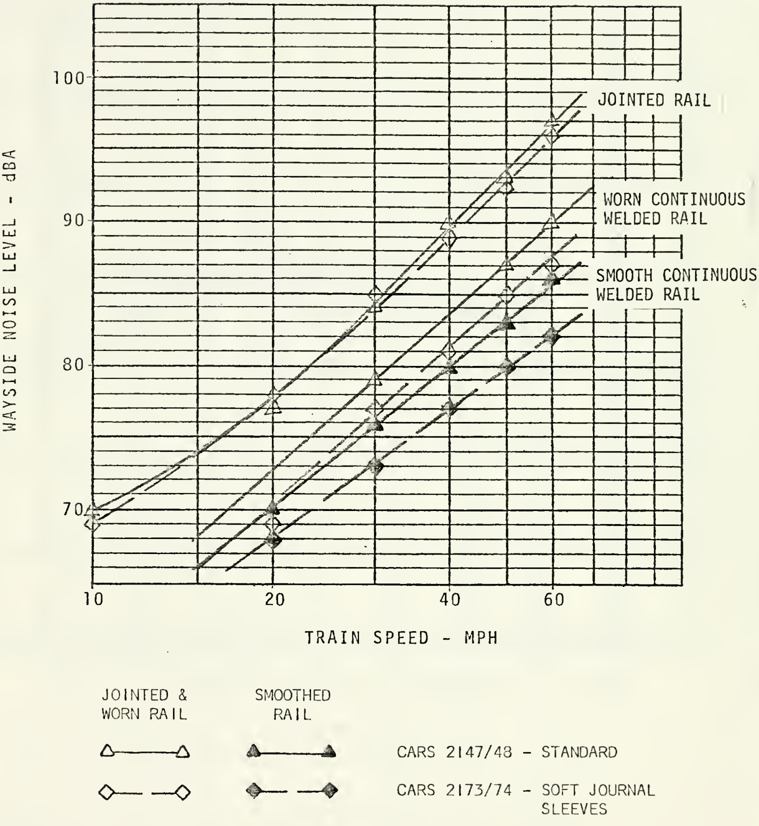


FIGURE 19 WAYSIDE NOISE LEVEL AT 50 FT FOR THE 2000 SERIES TRANSIT CARS ON VARIOUS RAIL CONFIGURATIONS

2-CAR TRAINS - BALLAST AND TIE TRACK

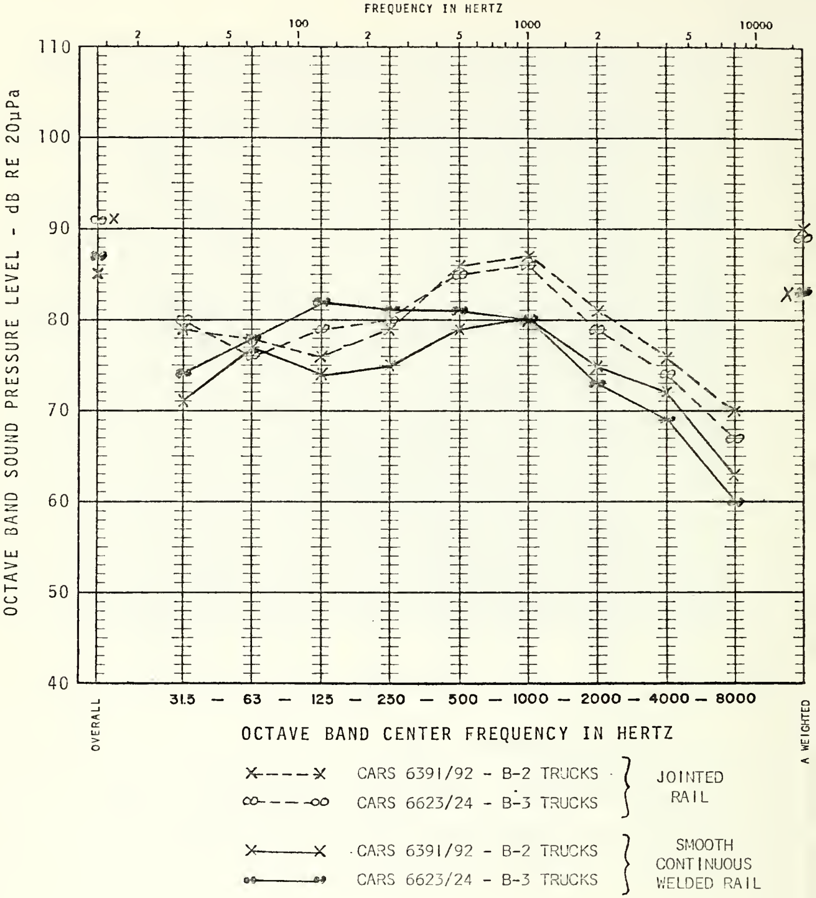


FIGURE 20 WAYSIDE NOISE LEVEL AT 50 FT FOR 6000 SERIES TRAINS ON BALLAST AND TIE TRACKS

2-CAR TRAINS - 40 MPH

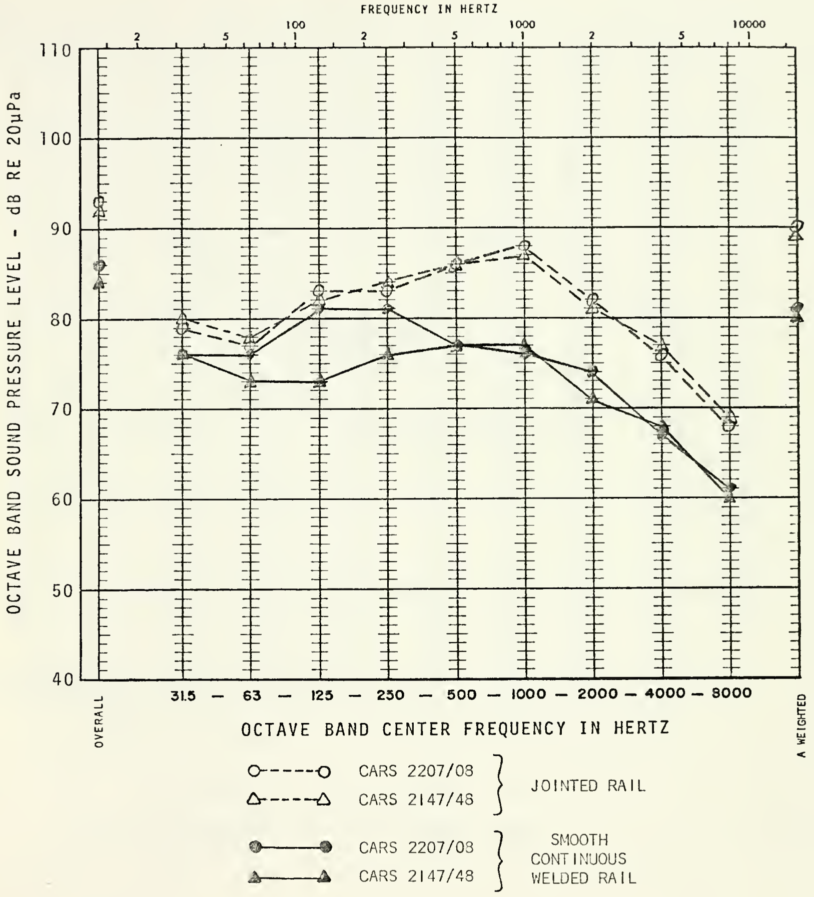


FIGURE 21 WAYSIDE NOISE LEVELS AT 50 FT FOR STANDARD 2200 SERIES AND OVERHAULED 2000 SERIES TRAINS ON BALLAST AND TIE TRACKS

2-CAR TRAINS - 40 MPH

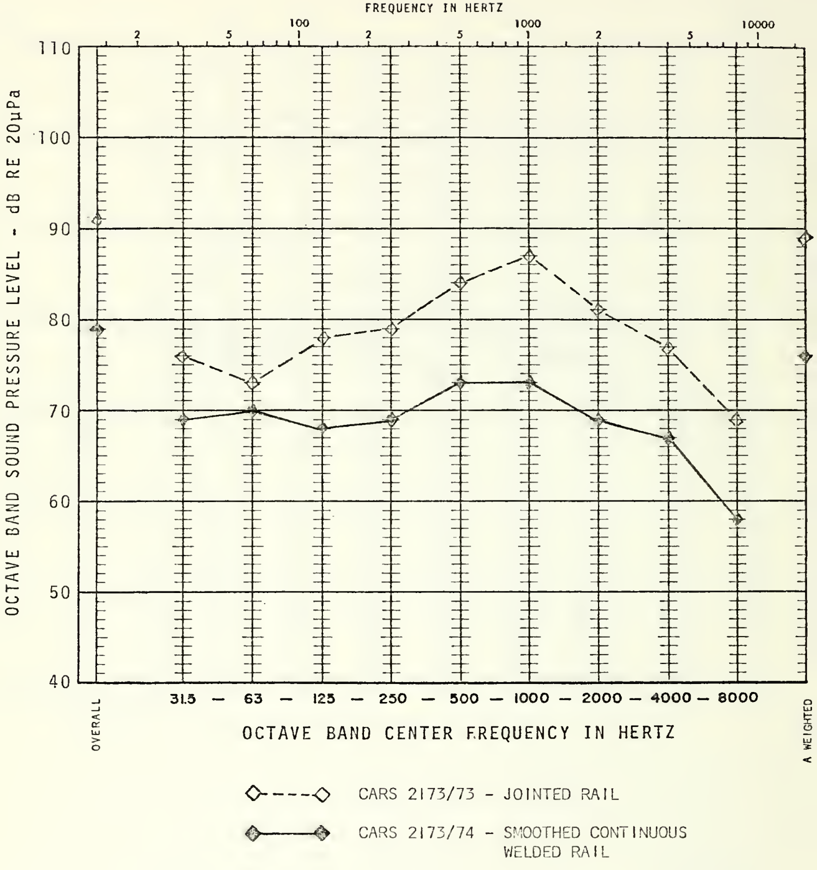


FIGURE 22 WAYSIDE NOISE LEVELS AT 50 FT FOR MODIFIED 2000 SERIES TRAIN - SOFT JOURNAL SLEEVES

2-CAR TRAIN - 40 MPH

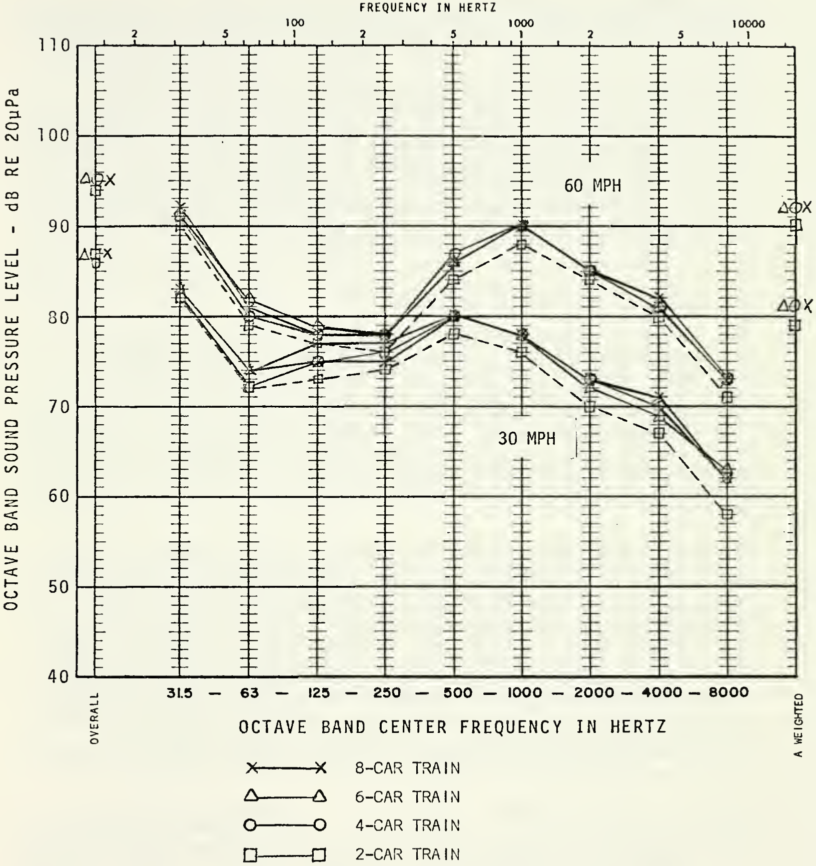


FIGURE 23 WAYSIDE NOISE LEVELS AT 50 FT FOR DIFFERENT LENGTHS OF 2000 SERIES TRAINS ON BALLAST AND TIE TRACK AT 30 AND 60 MPH

One further series of tests that was accomplished on the ballast and tie test section was the comparison of the wayside noise at 25 ft and 50 ft distance for trains longer than two cars. The measurements showed that for the wayside distances measured the long trains were about 2 dB higher in noise level than the 2-car trains but that there was little difference for the 4-, 6- and 8-car trains. Figure 23 presents the sound level data at 50 ft for the four different train lengths for 60 mph and 30 mph and graphically demonstrates the small difference in wayside noise which is found with longer trains of various lengths for identical operating conditions. Of course, at greater distances the long trains would result in higher sound levels than the short trains due to the greater sound power level of the longer trains.

C. Elevated Structure Wayside Noise

For the elevated structures, the wayside noise was measured at two characteristic types of structure: the open web structure and the solid web structure. The measurements were done using the standard 2000 and 2200 series cars and the specially modified 2000 series cars. Since the rail on the elevated structures is all jointed, only that configuration of rail was included in the test series. The detailed results of the wayside noise measurements at 50 ft and 25 ft from the elevated structure for the various types of transit cars are presented in Appendix A.

Figure 24 presents a summary of the wayside noise levels as a function of train speed for the various types of cars. There was little difference between the results for the different type of cars on the structures although there was greater difference than observed for operation of the transit trains on ballast and tie track with jointed rail. In general terms the 2200 series cars resulted in about 2 dBA less noise than for the standard 2000 series cars. The modified 2000 series cars with the soft journal sleeves gave essentially the same result as for the 2200 series cars. The differences between the solid web and open web structure were small with the solid web structure resulting in about 1 dBA greater wayside noise, on the average, than for the open web structure.

Figure 24 also includes notation of the expressions for the best straight line fit to the data. The mathematical relations are noted to the right of the car identification in the legend. As is shown on the charts the elevated structure wayside noise is proportional to $V^{3.9}$, about the same result as for the jointed rail on ballast. The difference between the two is, however, that operation on the elevated structure is 9 dBA more noisy on the average than for jointed rail on ballast. The range of the data for different cars on the elevated structure indicates typically 6 to 12 dBA more noise than for similar operations on ballast and tie jointed rail. The elevated structure wayside noise levels are typically 15 dBA and as much as 20 dBA greater than was observed for operation on the smooth continuous welded rail for the ballast and tie track.

Figures 25 and 26 present charts showing the typical octave band analyses for the train operations for both the solid and open web structures. The charts on Figure 25 are for the 2200 series and 2000 series standard trains and show the typical 2 dB less mid- and high-frequency noise for the 2200 series cars. Figure 26 shows the same comparison for the overhauled 2000 series cars and the cars with soft journals - little difference but slightly less noise with the soft journals. Both figures show that there is little difference between the structures except that the solid web structure produces more noise in the 63 and 125 Hz octave range.

The two sets of charts on Figures 25 and 26 show the major characteristics and differences in the performance of the various trains on the elevated structures. The octave band analyses represent the typical performance for 40 mph operation. Since the spectrum of the wayside noise varies little over the speed range from 30 to 50 mph, see Appendix A, the charts on Figures 25 and 26 can be used to represent typical performance. For speeds other than 40 mph the levels should be raised or lowered as indicated by the charts on Figure 24.

Figure 27 presents charts indicating the average differences in the performance of the two types of elevated structure and comparisons of the car performance. The upper chart shows the difference between solid web and open web for each car type, all giving about the same result, and showing the elevated structure type dominates the results. The lower two charts show the comparison between the standard 2000 series cars, 2059/60, with the 2200 series cars, 2207/08 and with the soft journal cars, 2173/74 - cars 2059/60 being noisier than both the other types by 1 or 2 dBA and several dB at low frequencies. The charts on Figure 27 are the averages for 30, 40 and 50 mph at both 25 ft and 50 ft.

D. Subway Wayside Noise

The detailed octave band analysis charts of the noise levels observed in the subways are given in Appendix C. Since these tests were done with revenue trains the conditions were much less controlled than for the measurements discussed in previous sections. Speeds of the trains were estimated by timing the passage of the trains with a stopwatch and all the analyses presented are for those trains which passed by at speeds of 30 to 40 mph. All of the tests were done at

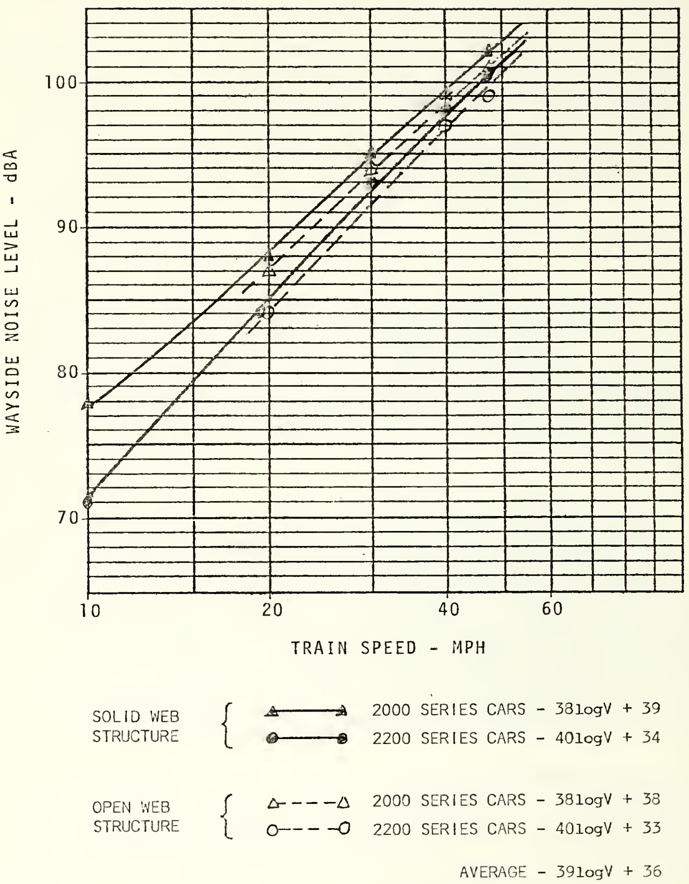


FIGURE 24 WAYSIDE NOISE AT 50 FT FROM TRACK CENTERLINE FOR OPERATIONS ON ELEVATED STRUCTURE

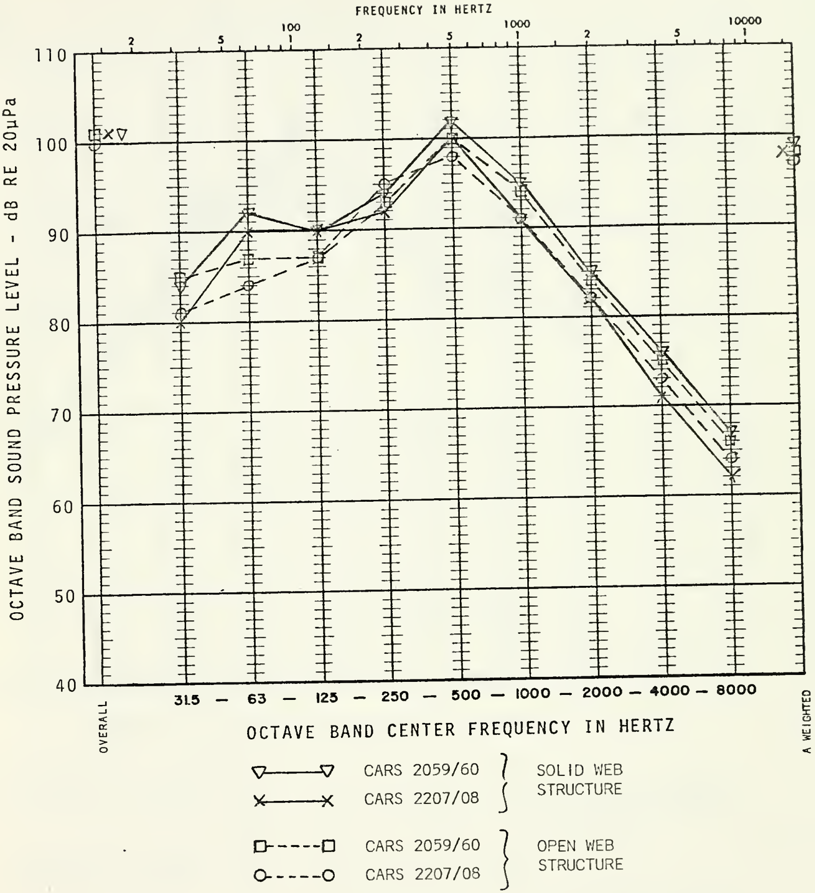


FIGURE 25 WAYSIDE NOISE AT 50 FT FOR STANDARD CONFIGURATION 2000 AND 2200 SERIES TRAINS ON ELEVATED STRUCTURE

2-CAR TRAINS - 40 MPH

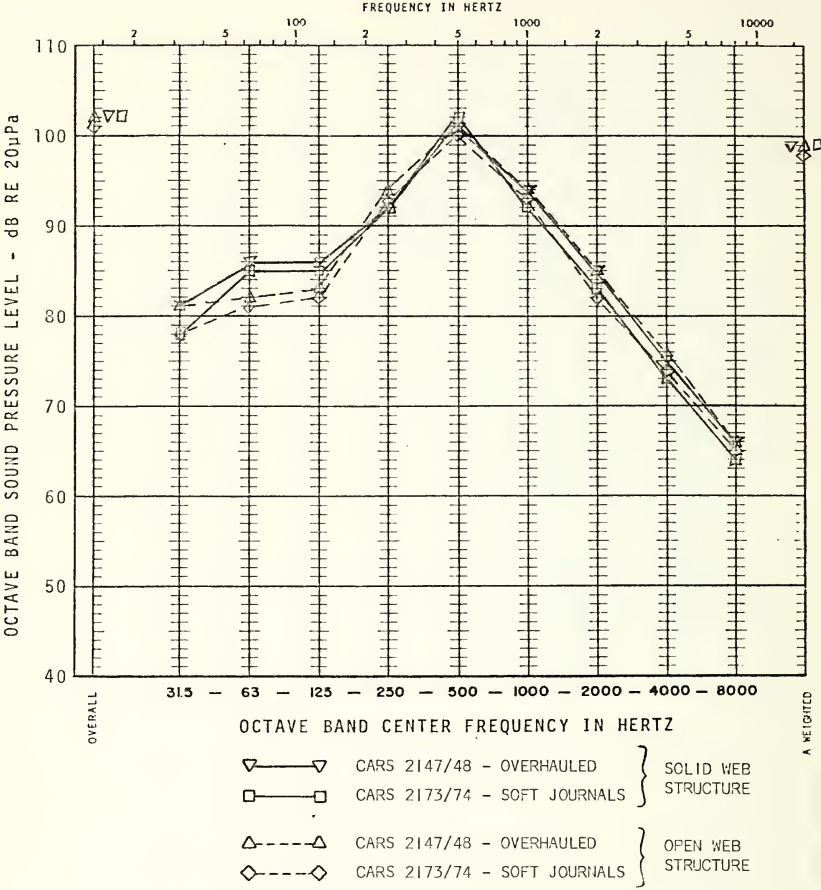


FIGURE 26 WAYSIDE NOISE AT 50 FT FOR OVERHAULED AND MODIFIED 2000 SERIES TRAINS ON ELEVATED STRUCTURE

2-CAR TRAINS - 40 MPH

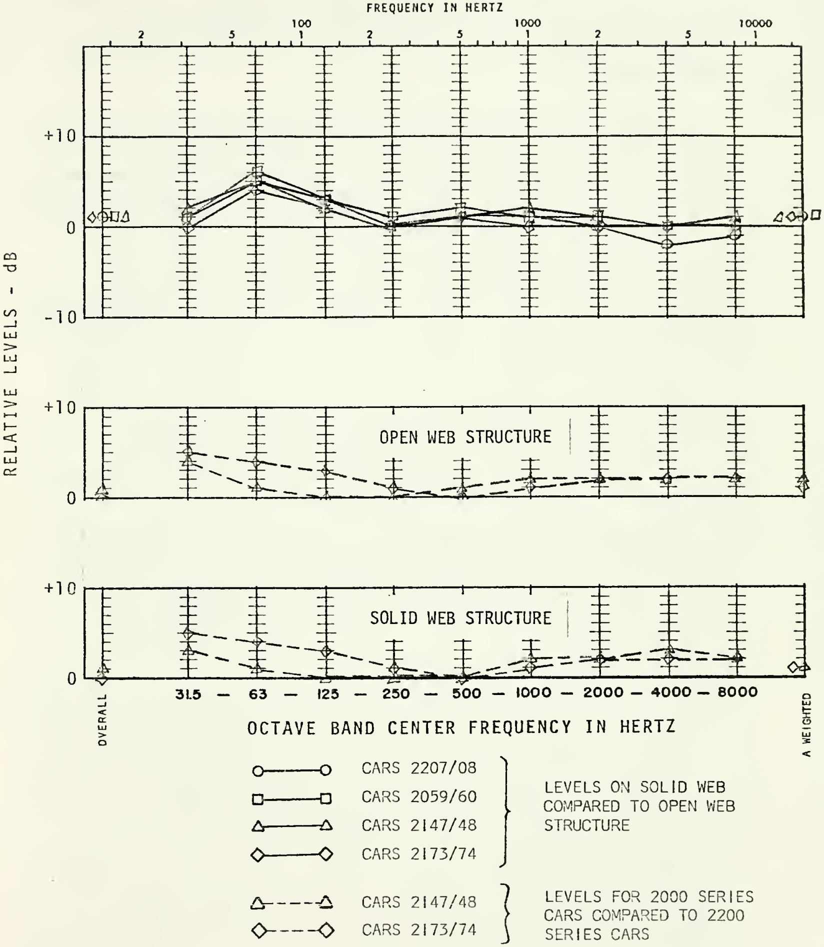


FIGURE 27 DIFFERENCE IN WAYSIDE NOISE FOR DIFFERENT TYPES OF CARS ON SOLID WEB AND OPEN WEB ELEVATED STRUCTURE

locations with continuous welded rail. Figure 28 presents octave band analyses of the average results for wayside noise in the subway sections considering both tunnels with concrete trackbed and the tunnel or box section with ballast and tie trackbed.

It is apparent from the charts on Figure 28 and in Appendix C that the noise level is considerably reduced outside the cars in the subways with ballast and tie track. Figure 29 is a chart indicating the differences in noise level observed in the subways with ballast and tie track compared to the subways with concrete trackbed, showing the overall average result for both subway configurations with ballast compared with the concrete trackbed tunnel configuration. The measurement results show an increase in the low frequency noise level, particularly for the tunnel configuration, for the range included in the 31.5 to 250 Hz octaves, and show a considerable reduction of the noise for the frequencies included in the 500 to 8000 Hz octaves. The overall result of this is a considerable reduction in the loudness of the noise since the mid-frequency range is the most intense and loudest part of the noise, i.e., the 500, 1000 and 2000 Hz octaves are the most important to the loudness of the noise. The small increase in low frequency noise, of greatest magnitude for the 125 Hz octave, is not significant in increasing the loudness of the noise since the more intense higher frequencies predominate in the subjective loudness of the noise.

The reduction in the noise level is apparently primarily due to the sound absorption created by the ballast. There could be some reduction in the noise radiated by the rail due to reduced vibration of the rail because of damping created by the ballasted trackbed. However, the measurements and calculations indicate that the total noise reduction observed can be explained by considering only the sound absorption effect of the ballast.

In order to determine the effective sound absorption coefficient of the ballasted trackbed, reverberation time measurements were made in the subway. Such a measurement provides a means for calculating the absorption of the ballast. Table VI indicates the measured reverberation times in the three types of subways, tunnels and box, along with the calculated absorption coefficients of the ballast. The absorption coefficients were derived using the characteristic dimensions of the subway and assuming the absorption of the concrete walls and ceiling were the same in all of the tunnels as was found for the tunnel with concrete trackbed. From these measurements and calculations of the effective absorption of the ballast it is possible to derive the expected noise reduction in the subway due to the sound absorption.

TABLE VI REVERBERATION TIMES AND BALLAST ABSORPTION IN SUBWAY TUNNELS

Frequency - Hz	125	250	500	1000	2000	4000
			REVERBERATION TIME - SECONDS			
Concrete Trackbed Tunnel	6.3	5.4	4.5	3.6	2.1	1.7
Ballast Trackbed Tunnel	1.1	1.4	1.05	1.35	1.2	1.0
Ballast Trackbed Box	.90	.95	.85	1.1	1.0	.95
			ABSORPTION COEFFICIENTS			
Concrete Tunnel Surfaces	.030	.035	.043	.053	.091	.113
Tunnel Ballast	.68	.52	.68	.46	.46	.47
Box Section Ballast	.67	.60	.67	.49	.40	.37

Figure 29 includes charts showing the expected noise reduction from the absorption for comparison with the actual reduced level of noise observed for the transit train operations. Two estimated level reductions are shown, one considering only that the sound level would be reduced due to the reduction of the reverberation in the tunnel. This assumes no specific relationship between the position of the sound source and the sound absorbing material. The indication is that for this consideration the noise reduction should have been only about 4 to 6 dB. The actual result was considerably more reduction than this, indicating that there are other factors influencing the noise level.

Because all of the noise sources on a transit train are beneath the car, in the confined space between the car and the trackbed, it is normal and appropriate to assume that with an absorptive trackbed the amount of sound energy radiated to the reverberant sound field will be reduced by the amount of sound energy absorbed at the first reflection from the trackbed. This then implies that the amount of sound energy available for the reverberant sound field should be reduced by an amount equivalent to the absorption coefficient of the ballast. The second calculated noise reduction curve on Figure 29 shows the amount of reduction expected with the addition of this assumption. Thus, the second calculated performance curve based on the absorption of the ballast includes the reduction due to the absorption of sound energy on the first reflection plus the reduction in sound level due to the reduction in the overall reverberation time of the subway. As is apparent from the chart this reduction amounts to about 10 dB over the mid-frequency range and is close to the measured result obtained with the transit trains.

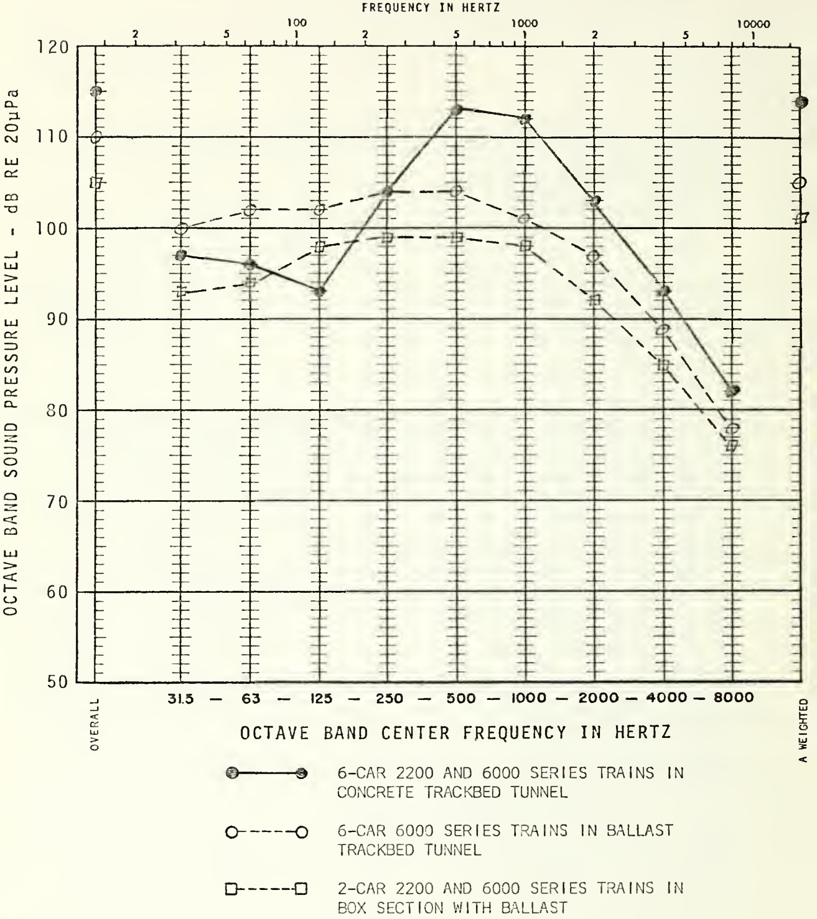


FIGURE 28 AVERAGE SUBWAY WAYSIDE NOISE LEVELS FOR 30-40 MPH OPERATIONS

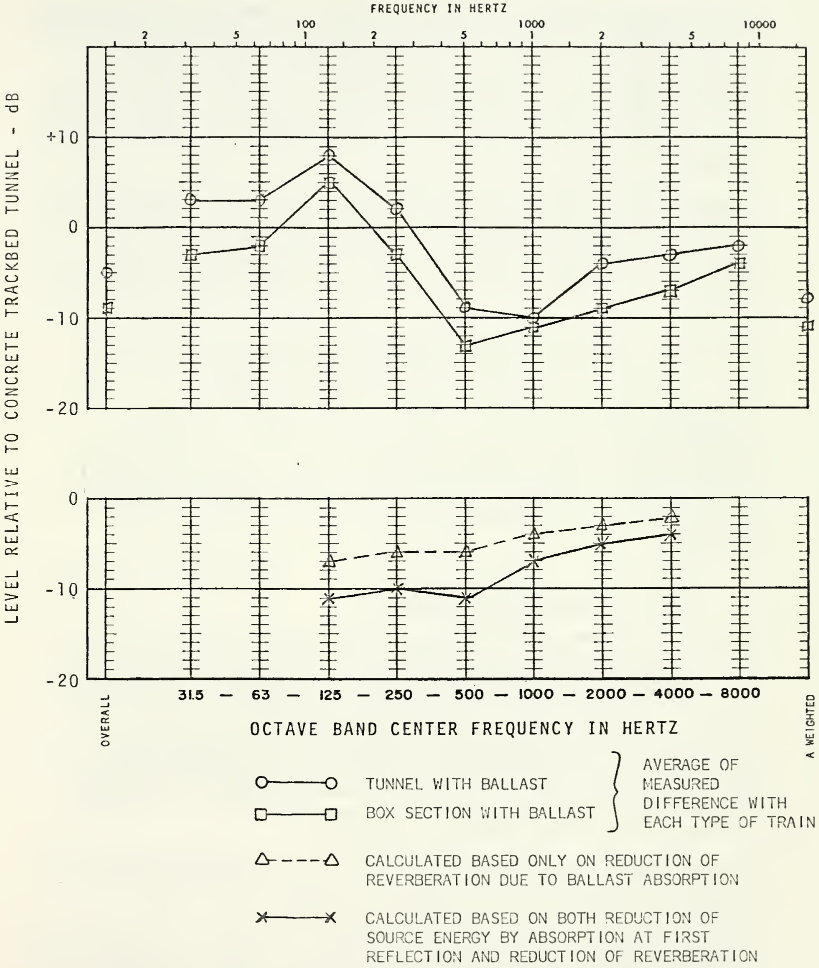


FIGURE 29 DIFFERENCE IN NOISE LEVEL IN SUBWAYS WITH BALLAST COMPARED TO CONCRETE TRACKBED TUNNEL

The results of the sound absorption measurements in the subways with ballasted track, compared to the noise measurements made with trains in concrete trackbed and ballasted trackbed subways indicate that the absorption characteristics of the ballast account for a major portion of the lower noise levels which result with the ballasted track. However, the estimates of the effect of the ballast as a sound absorber indicate that for the low frequency range there are other effects which predominate.

For the high frequency range included in the 1000 and 2000 Hz octaves there is, on the average, somewhat greater train noise reduction than predicted by the absortion analysis. This greater reduction in the upper frequency range could be due to additional noise reduction created by the track fastening system. It is possible that the ballast and tie track fixation system results in some damping of the rail, compared to the rigid fixation with concrete trackbed, with the result that there is somewhat lower radiation of noise from the rail. The greater low frequency noise created with the ballast and tie track could be due to difference in the track support modulus or stiffness. With the ballast the support stiffness is lower which could result in greater amplitudes of low frequency vibratory motion of the rails, trucks, and possibly the car bodies, thus producing a higher noise level at the source. Also with the ballast there may be some noise radiation from the ties which would not be present for the rigid rail fixation system with concrete trackbed.

E. Subway Platform Noise Levels

As for the subway wayside noise, the subway station platform noise levels were measured for revenue train operations and the conditions were less controlled than for the elevated structure and ballast and tie track measurements with special trains. Observations of the platform noise levels were made both for trains passing through the stations at constant speed and for trains entering, stopping and leaving the platform areas. The speeds of the trains, for those trains which passed through the stations, were estimated by timing the passage of the trains with a stopwatch and only those trains with similar speeds are reported.

The detailed octave band analysis charts of the platform noise levels due to the trains are given in Appendix D. Figures D1 through D4 give data for trains passing through stations and Figures D5 through D8 give data for trains which stopped at the station platforms. To obtain sound level measurements representative of all of the typical types of subway stations, measurements were made in both long and short platform tunnel stations with concrete trackbed, in a tunnel station with ballast and tie trackbed and in a box section station with ballast and tie trackbed. Measurements were made for trains operating both on the near track and on the far track with the microphone located at 5 ft from the edge of the platform and 4-1/2 ft to 5 ft above the platform. This position was chosen as representing a typical location for patrons waiting on the platforms.

Figures 30 and 31 present average or typical sound levels observed on the platforms for trains passing through the stations on the near track, Figure 30 and on the far track, Figure 31. The graphs on Figures 30 and 31 show the considerable difference in sound level which occurs in those stations with the absorptive ballasted trackbed compared to the tunnel stations with reflective concrete trackbed. Table VII is included to present in tabular form the typical A-weighted noise levels for the different stations and different types of trains.

TABLE VII TRAIN NOISE LEVELS ON SUBWAY STATION PLATFORMS WITH TRAINS PASSING THROUGH ON NEAR TRACK

Location	Train Type	Maximum Noise Level
State Street Subway Platform	8-car 6000 series	108 dBA
	6-car 6000 series	107
Dearborn Street Subway Platform	6-car 6000 series	105-106
	6-car 2200 series	105
Chicago Station Platform	6-car 6000 series	110
	6-car 2200 series	109
Clinton Station Platform - Ballasted Trackbed	2-car 6000 series	94
	2-car 2200 series	93
Belmont Station Platform - Ballasted Trackbed	2-car 6000 series	92
	2-car 2200 series	88-92

Table VII and Figure 32 show the comparative noise levels for the stations with ballasted trackbed compared to the tunnel stations with concrete trackbed. The charts on Figure 32 are similar to the charts on Figure 29 for the running tunnel noise levels. The measurement results for the two configurations show that in the subway stations the reduction in noise is even greater on the platform than for the running tunnels with ballasted track compared to concrete trackbed. The chart also includes the calculated noise reduction based on the absorption effectiveness of the ballast for the two conditions which can be assumed [1] simple reduction of the noise due to reduction of reverberation time and [2] reduction of the noise due to the combination of absorption at the source [through reduction of the sound energy at the first reflection] combined with reduction of the reverberation. Table VIII indicates the reverberation time measured in the various stations which were included in the noise measurement study.

TABLE VIII REVERBERATION TIMES MEASURED IN SUBWAY STATION TRAIN ROOM PLATFORM AREAS

Frequency - Hz	125	250	500	1000	2000	4000
Dearborn Station - Concrete trackbed	4.9	5.0	4.4	4.0	3.3	2.1
Clinton Station - Ballasted trackbed	0.9	1.6	1.25	1.4	1.6	1.3
Belmont Station - Avg - Ballasted trackbed	2.7	3.0	2.6	2.1	2.0	1.8

The noise reduction expected from the calculations based on the measured reverberation reduction and the source energy absorption of the ballast indicate that the measured noise reduction experienced is somewhat greater than the expected or calculated reduction. The results of the measurements in the subways indicate that the greater reduction is apparently not due to significant reduction in noise generation at the source through damping of the rail or other mechanism, but is due to absorptive effects of the ballast. In the case of the round tunnel station platforms, apparently the mid-frequency noise level, particularly the 500 and 1000 Hz octave ranges, is amplified or enhanced by focusing of the sound transmitted up from the trackbed and reflected by the round tunnel upper surfaces to the platform area. This effect is very pronounced in all the round tunnel stations with concrete trackbed. Because of the absorptive nature of the ballast, this focused reflection effect is virtually eliminated in the ballasted track stations. With the ballast, the sound is not reflected by the trackbed directly up to the round tunnel upper surfaces or ceiling, but rather is absorbed and the reverberant sound in the train room or platform area tends to be made up of less directive or more diffused reflected sound.

The net effect of the sound absorption contributed by the ballast in the ballasted track stations is to reduce the noise level from the transit trains on the platforms by about 15 dBA or by about 15 dB in the mid-frequency octaves where the noise is the most intense and subjectively the loudest. This is a very significant reduction of the noise and dramatically indicates the benefit of providing absorption at track level or under the platform in station platform areas to reduce the noise exposure of patrons.

No summarized charts of the noise from trains entering and leaving the platform are presented in this section because the noise levels experienced are highly dependent on the location of the observation point relative to the stopping point of the train. The charts on Figures D5 through D8 present typical results from measurements of trains entering, stopping and leaving the station platforms. In general, the maximum levels are similar to those for trains passing through when the train or a portion of the train passes by the observation point at relatively high speed. When a train enters and stops with the front just before or just at the observation point, the maximum noise during entering is relatively low and the noise as the train leaves is relatively high because the train builds up to relatively high speed at the observation point on leaving. The opposite is true when the train stops with the rear of the train near the observation point with the noise level being high during the approach of the train and low as the train leaves because it is some distance down the platform before achieving high speed. The effects of ballast or other absorption on reducing train noise are the same for trains entering, stopping and leaving as they are for trains passing through, as discussed above.

F. Car Interior Noise

The measurements of car interior noise provide data on the level of patron noise exposure in the cars for operation on the various types of way structures. Two basic types of measurements were made: [1] car interior noise levels for the car equipment with the cars on jacks, and; [2] car interior noise with the trains operating on various types of way

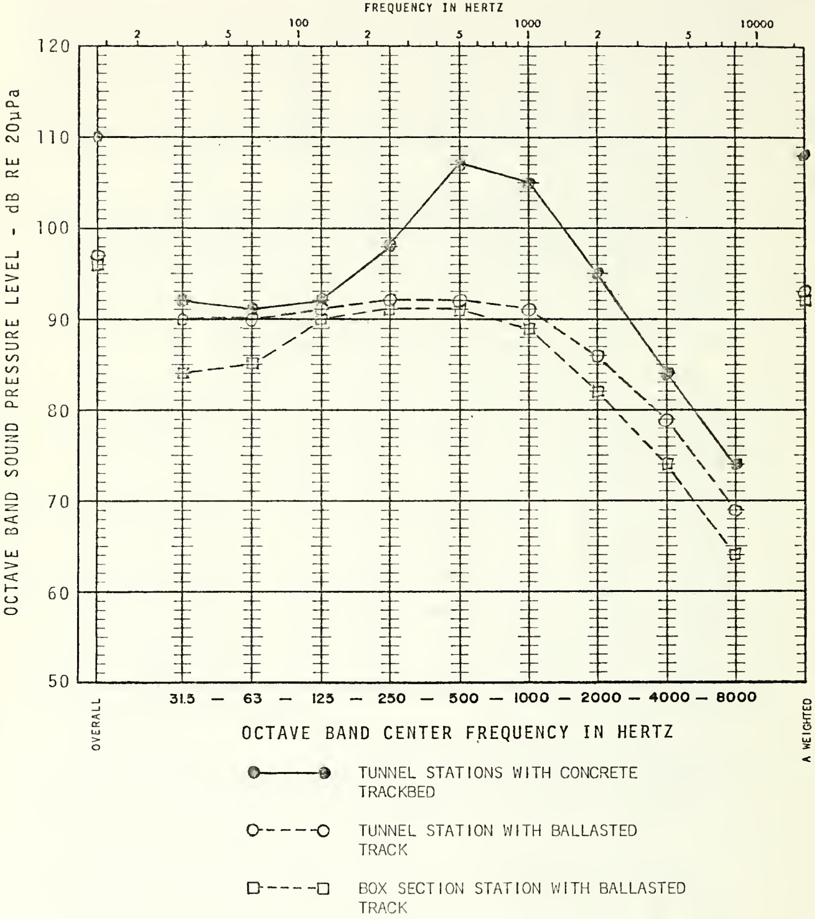


FIGURE 30 AVERAGE SUBWAY STATION PLATFORM NOISE LEVELS WITH TRAINS PASSING BY ON THE NEAR TRACK AT 30-40 MPH

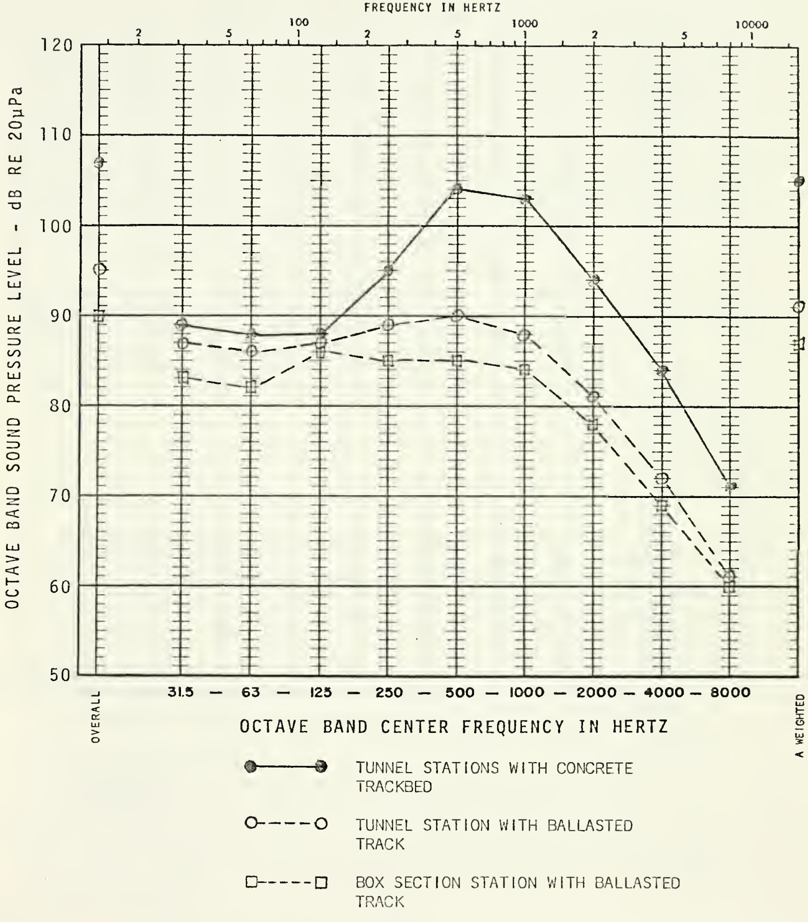


FIGURE 31 AVERAGE SUBWAY STATION PLATFORM NOISE LEVELS WITH TRAINS PASSING BY ON THE FAR TRACK AT 30-40 MPH

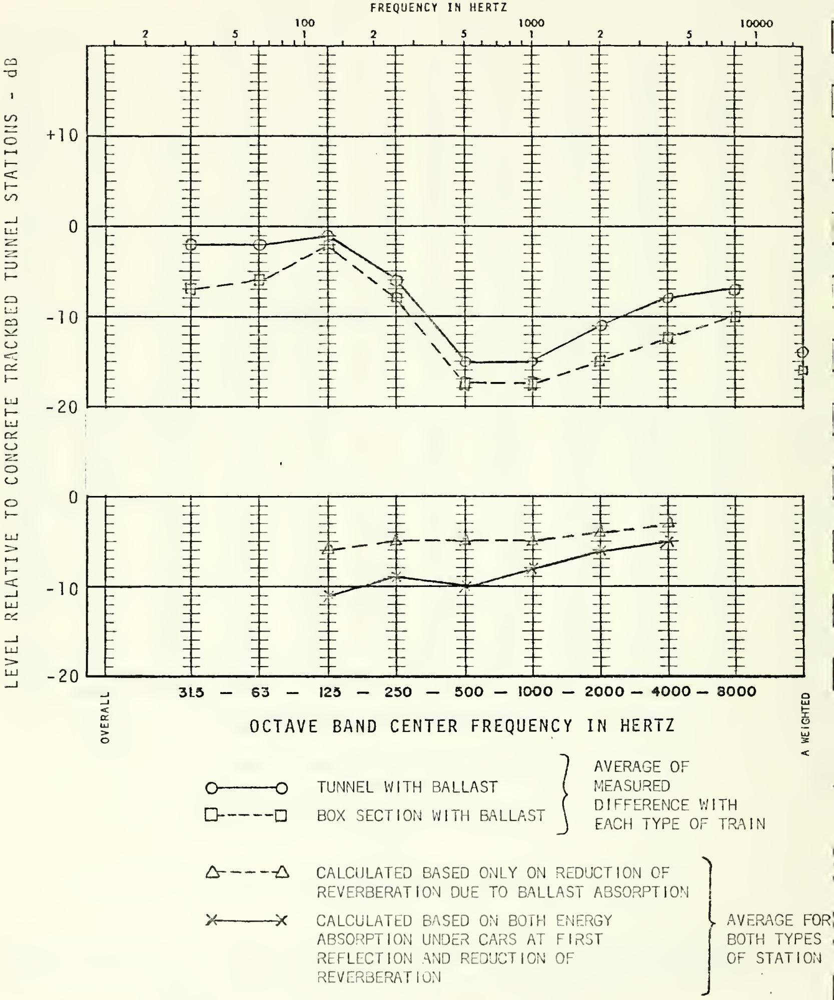


FIGURE 32 DIFFERENCE IN PLATFORM NOISE LEVELS IN SUBWAY STATIONS WITH BALLASTED TRACK COMPARED TO TUNNEL STATIONS WITH CONCRETE TRACKBED

structure including subway, elevated structure and ballast and tie track. The results of the measurements of car interior noise levels due to the car equipment, including both the propulsion equipment and the auxiliary equipment, are presented in Appendix G. The car interior noise levels for operations on elevated structure and ballast and tie track are presented in Appendix E and the interior noise levels for operations in subways are presented in Appendix F.

This section of the report presents charts and discussion summarizing the results from the car interior noise measurements including comparison of the noise levels experienced by patrons for various operating conditions and way structures.

1. Car Equipment Noise

As for the car equipment wayside noise, the car interior noise due to equipment only was measured with the cars located in the Harlem Shop Building on jacks and with the wheels spinning or with each of the auxiliary equipment items operating independently. The results of these measurements are given in Appendix G. Table IX and Figures 33 and 34 present summarized data for the propulsion equipment noise. Figure 35 indicates car interior noise for the noisiest of the auxiliary equipment to show the magnitude of auxiliary equipment noise compared to propulsion equipment noise and to the car interior noise from wheels and rails with the trains operating on running track, as presented later in this section.

In the discussion of car equipment wayside noise, it was indicated that the major portion of the noise generated by transit car propulsion systems is the noise associated with the drive motors. The noise from the motors is predominantly the turbulent airflow noise caused by the cooling airflow and normal motor windage noise, a noise which is independent of load on the motor. There is, of course, some general machinery noise accompanying the air noise. All of the noises generated by the propulsion equipment are dependent on speed, however, it does appear that the cooling airflow noise predominates, at least at the higher speeds. The data on Figure 33 includes the mathematical expression of the straight line which best fits the data, within 1 dB, over the speed range covering the normal operation of the cars. The indication is that the noise inside the cars is proportional to the 4.5 power of the motor speed with the noise in the 6000 series cars about 2 dBA greater than for the 2000 and 2200 series cars. This speed dependence result is very similar to that found for the wayside noise and is in the range of expected results for air cooled electric motors.

TABLE IX CTA TRANSIT CAR INTERIOR NOISE LEVELS DUE TO PROPULSION SYSTEMS - MEASURED WITH THE CARS ON JACKS AND WHEELS SPINNING

		Noise Level	
Car	Speed	At Car Center	Over #2 Truck
2207	40	71 dBA	70 dBA
	55	75	76
	70	84	85
2060	35	66	68
	50	73	74
	70	86	87
6624	35	69	71
	50	76	78

It must be noted that the results for the propulsion equipment noise shown on Table IX and on Figures 33 and 34 represent the noise as transmitted into the cars in a reverberant room. Therefore, the levels are higher than would be expected for the equipment noise in the car when operating on ballast and tie track or on open deck elevated structure. This is true because in the shop building the sound from the equipment was reflected from the concrete floor and the walls and ceiling of the building with the sound consequently being transmitted through the car walls and ceiling as well as the car floor.

For operation on ballast and tie track or open deck elevated structure there is little reflection of the sound from the trackbed and virtually no transmission through the transit car walls and ceilings from these particular noise sources. Thus, the levels would be expected to be lower than measured in the shop test situation. Conversely, for operation in subway with concrete trackbed the reflection and reverberation would be greater than experienced in the large shop building, because the tunnel surfaces are closer to the transit car in the subway. Therefore, for subway operation it would be expected that the equipment noise levels inside the car would be equivalent to or somewhat higher than the levels reported in Table IX and Figures 33 and 34. Thus, it is apparent that the data presented for the car interior noise due to the propulsion equipment represent levels that are somewhere between the levels which would be expected for normal operation on ballast and tie tracks or elevated structure and the levels for operation in subway with concrete trackbed. Probably the measured results are very close to those for operation in subway with ballast and tie trackbed.

The interior noise due to auxiliary equipment is shown on Table X and Figure 35. The same comments with regard to the levels of the noise for the undercar equipment apply as were indicated above for the propulsion equipment noise, i.e., the noise for the undercar equipment is higher in level than would be experienced with the cars operating on ballast and tie track or open deck elevated structure and are lower in level than for operation in a concrete trackbed subway. However, for the auxiliary equipment which generates noise within the car body, i.e., ventilation fans and air conditioning system air circulation components, the noise levels shown are correct and represent the values which would be expected under any operating circumstances for the car. Since the noise is generated inside the car, the type of way structure on which the car is located has essentially no effect on the noise from the air circulation blowers or fans.

TABLE X CTA TRANSIT CAR INTERIOR NOISE LEVELS DUE TO AUXILIARY EQUIPMENT - MEASURED WITH THE CARS ON JACKS IN A SHOP BUILDING

		Noise Level	
Car	Equipment Item	At Car Center	Over #2 Truck
2207	Air Conditioning System and Ventilation Fans	69 dBA	65 dBA
	Ventilation Fans Only	63	59
	Inverter and Lights	51	51
2060	Full Air Conditioning System Operating	72	73
	Low Cooling Rate A/C	68	68
	Air Circulation Fans Only	65	65
	Inverter and Lights	49	45
2059	Air Conditioning System	72	67
	Inverter	57	55
	Converter	49	47
6624	Motor Generator and Ventilation Fans	63	63
	Ventilation Fans	51	54

Comparing the data for the auxiliary equipment noise levels inside the cars with noise levels from the propulsion equipment [and with noise levels for operation on the various types of way structure as presented later in this section of the report] show that, with the exception of the air conditioning system and air circulation fans, the auxiliary equipment generates less noise than propulsion or wheel and rail noise for most normal operating conditions. There are some operating conditions for which the air conditioning systems do generate greater noise. The equipment noise, therefore, represents the minimum level in the cars during operation when the air conditioning systems and circulation fans are functioning. Even though the air conditioning system or air circulation fan noise is the predominant noise for some modes of operation, i.e., low speed or stops at station platforms and for some operations on ballast and tie track, in general the car interior noise during operation is considerably higher than that due to the air conditioning systems. The air conditioning system noise is, therefore, not predominant during the major part of the patron's noise exposure during a cycle of entering, riding on and leaving the transit cars.

2. Car Interior Noise During Operations

For convenience in presentation of the summarized results of car interior noise for operations on ballast and tie track, elevated structure and in subway, the tables, charts and discussion for all three types of operation are combined together in this subsection. Since most of the car interior noise measurements were made with the test trains operating between revenue service trains the measurements were less well controlled than for the elevated structure and ballast and tie track wayside noise measurements. The 2000 series trains were operated on ballast and tie track, elevated structure and subway on the Congress and Milwaukee Lines, the 6000 series trains on elevated structure and ballast and tie track on the Howard Line and the 2200 series train was operated on the elevated structure on the Lake Line, in subway and on elevated structure on the Congress and Milwaukee Lines and on ballast and tie track and elevated structure on the Howard Line. Thus the interior noise levels were not all measured on the same section of track for all trains as was done with wayside noise.

There are some combinations of cars, types of structures, and speeds which are not included in the test results because of limitations on time or on length of way structure sections at the time of the test runs. The results were also dependent somewhat on the condition of the running rails at the different test sections, since the tests for each pair of cars were not necessarily run at the same section of track.

Tables XI, XII and XIII present the summarized data for the car interior noise levels at 30, 40 and 50 mph. For most of the tests, runs were accomplished at both 30 and 50 mph, however, for some of the types of way structure, there were no runs made at 40 mph. Figures 36 through 40 present summarized data for the car interior noise levels on ballast and tie track, Figures 41 through 44 present summarized data for operations on elevated structure and Figures 45 through 49 present the summarized data for operations in subway, both concrete trackbed and ballast and tie track and for running tunnels and operation through stations.

For the ballast and tie track tests some of the car interior noise tests were done on the "test track" area of the Howard Line, the 2200 series train and the two 6000 series trains, and as a result the data for these cars is more complete. The individual data charts for the car interior noise on ballast and tie track are given in Appendix E, Figures E12 through E29. Data is included for operations on jointed rail, worn continuous welded rail and smoothed continuous rail. There are also some data charts giving noise levels experienced when operating through a ballast and tie track crossover. The data presented in most of the charts is the average of the measurements results over the car center and over #2 truck of the car in which the microphones were located. Figures E20 and E21 show the individual data at the car center and over the #2 truck to indicate the typical range or difference of noise levels from the center to the ends of the cars.

TABLE XI 2200 SERIES CAR INTERIOR NOISE LEVELS. THE LEVELS INDICATED ARE THE AVERAGE OF THE MEASUREMENTS AT THE CAR CENTER AND #2 END

Way Structure Type	30 mph	40 mph	50 mph
CAR 2207			
Tunnel - Concrete Trackbed	89 dBA	-- dBA	96 dBA
Tunnel - Ballast Trackbed	82	87	91
Box Section - Ballast	82	--	87
Tunnel Station - Concrete	88	--	--
Box Section Station - Ballast	80	--	86
Solid Web Elevated - 2-Track	86	90	95
Open Web Elevated - 2-Track	82	86	--
Solid Web Elevated - 4-Track	81	85	87
Jointed Rail - Ballast & Tie	82	85	88
Worn Welded Rail - Ballast & Tie	78	82	83

TABLE XII 2000 SERIES CAR INTERIOR NOISE LEVELS. THE LEVELS INDICATED ARE THE AVERAGE OF THE MEASUREMENTS AT THE CAR CENTER AND #2 END

Way Structure Type	30 mph	40 mph	50 mph
CAR 2060			
Tunnel - Concrete Trackbed	91 dBA	-- dBA	98 dBA
Tunnel - Ballast Trackbed	88	--	93
Box Section - Ballast	85	--	90
Tunnel Station - Concrete	90	94	97
Tunnel Station - Ballast	86	--	91
Box Section Station - Ballast	84	--	89
Open Web Elevated - 2-Track	90	94	98
Worn Welded Rail - Ballast & Tie	82	86	89
Smooth Welded Rail - Ballast & Tie	81	83	87
CAR 2147 - Overhauled			
Tunnel - Concrete Trackbed	92	95	98
Tunnel - Ballast Trackbed	84	--	90
Box Section - Ballast	83	--	88
Tunnel Station - Concrete	89	93	95
Tunnel Station - Ballast	83	--	89
Box Section Station - Ballast	81	--	86
Open Web Elevated - 2-Track	90	94	97
Worn Welded Rail - Ballast & Tie	81	84	86
Smooth Welded Rail - Ballast & Tie	80	82	85
CAR 2174 - Soft Journals			
Tunnel - Concrete Trackbed	88	--	97
Tunnel - Ballast Trackbed	80	--	85
Box Section - Ballast	78	--	83
Tunnel Station - Concrete	86	87	89
Tunnel Station - Ballast	78	--	83
Box Section Station - Ballast	74	--	78
Open Web Elevated - 2-Track	87	--	96
Worn Welded Rail - Ballast & Tie	74	77	81
Smooth Welded Rail - Ballast & Tie	72	75	78

TABLE XIII 6000 SERIES CAR INTERIOR NOISE LEVELS. THE LEVELS INDICATED ARE THE AVERAGE OF THE MEASUREMENTS AT THE CAR CENTER AND #2 END

Way Structure Type	30 mph	40 mph	50 mph
CAR 6624 - B-3 Trucks			
Tunnel - Concrete Trackbed	94 dBA	96 dBA	-- dBA
Tunnel Station - Concrete	91	--	--
Solid Web Elevated - 4-Track	84	88	90
Jointed Rail - Ballast & Tie	81	83	84
Smooth Welded Rail - Ballast & Tie	79	82	83
CAR 6392 - B-2 Trucks			
Tunnel - Concrete Trackbed	94	95	96
Tunnel Station - Concrete	89	--	--
Solid Web Elevated - 4-Track	83	87	89
Jointed Rail - Ballast & Tie	78	83	84
Smooth Welded Rail - Ballast & Tie	75	78	80

It is apparent from the charts on Figures 36 and 37 that the speed dependence of the car interior noise when operating on ballast and tie way structure is considerably different than the speed dependence for the wayside noise or for the car equipment noise transmitted to the car interior. On the jointed rail and the worn or corrugated continuous welded rail the car interior noise is proportional to $V^{2.5}$. The best fit curves cover the range of $V^{2.4}$ to $V^{2.6}$ for the 6000, 2200 and 2000 series cars except for car 2174 with soft journals which was quieter and showed a speed dependence proportional to $V^{2.9}$.

The car interior noise results contrast to the jointed rail and worn rail results for wayside noise which showed a dependence between $V^{3.5}$ and $V^{3.9}$. The difference in these two results is due to the sound insulation characteristic of the car bodies which cause a change in the sound spectrum, lowering the frequency range which is important or predominant in the loudness or A-weighted sound level of the noise. The car body sound insulation is more effective in the mid- and and high-frequency range than in the low frequency range. Thus, where the high-frequency range, [the 1000 to 2000 Hz octaves] predominates in the wayside noise, for the car interior noise the spectrum level is lower at the high frequency end and the predominant part of the noise is the 250, 500 and 1000 Hz octave range.

Examination of the octave band analysis charts for different speeds of operation shows that the low frequency noise changes less rapidly with speed than the high frequency. This provides one explanation for the lower variation of car interior noise with speed than is found for the wayside noise. Another reason is that the background noise inside the cars starts at a higher level for low speed or stopped operation than is the case for wayside noise. Thus, the background noise inside the trains influences the rate of change of noise level with speed. Also, the car interior noise has contributions both from airborne noise transmitted through the floor and body panels and from solid- or structure-borne noise transmitted from the trucks to the car body. Structure-borne noise could affect the results causing higher noise levels at low speeds than would result with only airborne noise contributing to the interior noise.

As is evident from the noise level charts on Figures 36 and 37 and the octave band analysis charts on Figure 38 there is little difference in interior noise levels for the 6000 series cars with B-2 or B-3 trucks for operation on the jointed rail. The car with B-3 trucks gave little reduction of the noise when operating on smooth continuous welded rail relative to the jointed, rail, however, the car with B-2 trucks did give a significantly lower level of interior noise when operating on smooth continuous welded rail. The standard 2000 series cars actually gave slightly higher noise levels on jointed rail than either of the 6000 series trains tested. The 2200 series train was not tested on smooth continuous rail but gave about 4 dBA less noise on the worn continuous rail than for jointed rail.

The largest contrast in car interior noise for ballast and tie track operation is found in the data for the 2000 series cars, as is shown by the octave band graphs on Figure 39 and the noise versus speed charts on Figure 36. The unmodified 2000 series cars were found to have higher interior noise level than either the 2200 series or 6000 series cars on worn or smooth continuous welded rail. In fact, the unmodified 2000 series car interior noise level on worn continuous welded rail is comparable to the 2200 and 6000 series trains on jointed rail. The 2000 series cars with the overhauled and modified trucks showed some reduction in the noise compared to the unmodified, although not by a significant amount in terms of A-weighted sound level. The difference was largely in the 250 Hz and lower octaves and this range showed a 5 to 7 dB lower noise level than for the unmodified car.

The 2000 series car with the modified trucks and with the soft journals resulted in much quieter operation in terms of interior noise for all of the tested conditions and the best improvement was in terms of the interior noise when operating on smooth continuous welded rail. The speed dependence for the noise on the modified 2000 series cars with soft journal sleeves was closer to the same dependence for the wayside noise, i.e., $V^{2.9}$, thus it is apparent that most of the noise transmitting into the cars for operations with the soft journal sleeves was airborne noise with less solid-borne or structure conducted sound contributing to the noise level at all speeds. This, of course, is one result that could be expected from the insertion of a softer rubber mount which would tend to reduce solid-borne or structure-borne conduction of sound and vibration. It is interesting to note, on Figure 37, that the 6000 series cars with B-2 trucks also result in noticeably lower noise level on the smooth continuous welded rail. This could be the result of softer primary springing.

The measurements of car interior noise for operations on elevated structure included 2-track open web structure, 2-track solid web structure and 4-track solid web structure. The results of the tests, as with the wayside noise, showed that the noise is more dependent on car type than on structure type. Further, the results showed that rail condition was more significant in affecting the noise level than the structure type. The measurements for the 2200 series train included observations on 2-track open web structure on the Loop and Milwaukee Lines, 2-track solid web structure on the Lake Line and 4-track solid web structure on the Howard Line. The 2-track open web structure and the 4-track solid web structure measurements gave about the same levels [see Figures 41 through 44]. The solid web 2-track structure, however, resulted in 4 to 9 dB more car interior noise than for the other elevated structure operations, the speed dependence of the noise was also greater, indicating greater dependence of the car interior noise on airborne noise from the wheel/rail interaction.

The charts on Figures 41 and 42 include the expressions of the speed dependence for the elevated structure car interior noise in the same manner as for the ballast and tie interior noise and the wayside noise previously discussed in this report. As is apparent from these charts, the 2000 and the 6000 series trains on the 2-track elevated and 4-track elevated resulted in noise levels proportional to $V^{2.9}$, a somewhat greater dependence than that found for operation on the jointed and worn continuous welded rail ballast and tie track tests. For the elevated structure operations the interior noise in the 2200 series was the quietest for all those tested. The 6000 series cars were 1 to 3 dBA noisier than the 2200 series. On the elevated structure the 2000 series gave the highest interior noise levels, being 6 to 9 dBA noisier than the 2200 series and 5 to 7 dBA noisier than the 6000 series cars for operation on the same elevated structures.

The main differences observed for the car interior noise on elevated structure are that [1] the level is somewhat dependent on the car type and [2] the level is very dependent on the rail condition. Structure type has little effect. The main difference observed was that on a 2-track solid web structure the 2200 series cars had interior noise proportional to $V^{3.9}$ which correlates very well with the wayside noise speed dependence. This indicates that the noise was predominantly due to airborne noise transmitted into the car from wheel/rail interaction and structure vibration generated noise. For the remainder of the conditions tested the speed dependence was close to $V^{2.9}$, indicating a combination of airborne and structure-borne noise transmitted into the cars.

It is also interesting to note that there was virtually no difference in car interior noise level on the elevated structure for the various configurations of 2000 series cars. At the most the modified cars with the soft journal springs gave 2 to 3 dBA reduction of car interior noise. This result lends support to the conclusion that the higher noise levels in the 2000 series cars on elevated structure are due to the transmission of airborne noise through the car body and floor panels. The other measurements for the cars with soft journal springs all show decreased interior noise due either to reduced transmission by structure-borne paths to the car body due to the soft journal pads, or due to reduced noise generation at the source because of effective lower unsprung weight, or a combination of these effects. On the elevated structure these effects have virtually no influence indicating that the vibration levels of the elevated structure are similar even with the soft journal sleeves, that the airborne noise generated by the elevated structure vibration predominates and that the noise is transmitted into the 2000 series cars at higher levels than for the other two series of cars.

The measurements of car interior noise levels for subway operation indicated the highest noise levels found for all types of operation. The highest levels were found for operations in the smooth bore concrete tunnels with concrete trackbed. As with the elevated structure operations the levels for the 2000 series cars were the highest except for the 6000 series in concrete trackbed tunnels. However, in this case, unlike with the elevated structure, the modified versions of the 2000 series cars had lower noise levels, particularly in ballasted trackbed subways. Figures 45 and 46 show the car interior noise levels observed for operations in the smooth bore tunnels with concrete trackbed, the tunnels with ballasted trackbed and the box sections with ballasted trackbed. Figure 47 shows the same data for operations through stations.

For the subway measurements, with the exception of one set of readings for the 2200 series cars, all of the noise levels were found to have a speed dependence in the range of $V^{2.4}$ to $V^{3.0}$. For the concrete trackbed tunnels the car interior noise is proportional to $V^{2.9} - V^{3.0}$ and in both the tunnel with ballast and the box section with ballast the results indicate a speed dependence very close to $V^{2.4}$.

In the tunnels with concrete trackbed the modified 2000 series trains gave somewhat reduced noise levels, 1 to 3 dBA, compared to the standard or unmodified cars, however, the difference was not significant and all three series of cars measured gave about the same level at the same speed, see Figure 48. Of the standard configuration cars, the 2000 series was quietest although by only about 2 dBA. In strong contrast, for operations in the ballasted track tunnels the modified cars, particularly the cars with the soft journal sleeves, had substantially lower interior noise level, 7 to 9 dBA less noise than for the unmodified 2000 series cars. It should be noted that all of the tests for the 2000 series in subway were run on the same day with each of the three configurations of trains operating over the same section of rail. The results, therefore, are representative of differences in the car characteristics and are not influenced by any differences in the running rail for the different measurements.

Figure 48 indicates the typical octave band noise levels for the three series of cars operating in tunnel with concrete trackbed. There was little difference between the two types of 6000 series trains tested, and little difference between the various configurations of the 2000 series trains as noted above. Therefore, for the chart the averages of the 6000 cars with B-2 and B-3 trucks and the average of the 2000 series standard and overhauled cars were calculated and are presented to show typical performance at 40 mph.

Figure 49 shows the octave band analysis of the car interior noise levels for the 2000 series and 2200 series trains operating in subway with ballast and tie track. There was very little difference found between the box section and the tunnel with ballast except that for operating in the tunnels the average levels were about 2 dB greater than in the box section for the same operating conditions. The octave band spectra are very similar in shape, see Figures F5 through F8. Since the results were so close together the charts on Figure 49 show the average of the results for the two types of ballasted subway. To convert to the individual results, for the tunnels the levels should be 1 dB higher and for the box section the levels 1 dB lower. The charts show normalized or average results for 40 mph operation and to convert to levels for other speeds of operation, both on Figure 48 and on Figure 49, the levels should be adjusted upward for higher speeds and downward for lower speeds as indicated by the charts on Figures 45 and 46.

The noise levels experienced in the cars when passing through stations, either with concrete trackbed or ballasted trackbed, are about 2 dB less than for traveling in subway of the same type, as is indicated on Figure 47. Comparison of the octave band analysis charts for the operation through the subway stations and for operation in the running tunnels, as shown on the charts in Appendix F, indicates again that there is very little difference in the spectrum shape, thus, the octave band charts shown on Figures 48 and 49 are similar to those for operation through the subway stations, except that the levels sould be lowered by about 2 dB for the station operation. The lower noise levels experienced while operating through stations are due to the larger space and lower reverberant sound level which occurs in the stations compared to the running tunnels. This results in a slightly lower sound level being imposed on at least the upper parts of the car body giving slightly reduced sound levels inside the transit cars.

Figure 50 presents two sets of charts indicating relative performance of the trains in the subway structures. The upper set of curves on the figure indicate, for each set of cars tested, the noise levels in the ballast and tie subways relative to the tunnels with concrete trackbed, an indication of the difference in subway structure performance. In all cases, for the ballast and tie subway the car interior noise is of greater level for the low-frequency octaves and of lower level for the mid- and high-frequency octaves. This results in a considerable reduction of the loudness of the noise. The charts also show very similar performance for all the configurations and types of cars indicating that the difference between the ballast and tie subway and the concrete trackbed subway, i.e., the sound absorption, results in about the same interior noise level reduction regardless of car characteristics. This indicates that any future changes in the running tunnels or subway stations for noise reduction would give approximately the same reduction of interior noise for each of the various types of transit cars.

The charts on the lower half of Figure 50 indicate the relative performance of the different types of transit cars in the ballasted subways and, therefore, give a measure of the difference in performance of the different configurations of cars. As is shown on Figure 48, there is little difference in the noise levels for the standard car configurations in the concrete trackbed subway. Figures F1 and F2 do show there is some difference for the modified 2000 series cars, with somewhat lower levels being experienced in the overhauled cars with the soft journal sleeves, although the differences are not nearly so great as for the ballasted track subways as shown on Figure 49.

The lower charts on Figure 50 present the results for the different car configurations in the ballasted subway in a manner to show noise level in the cars relative to the 2200 series car. The charts show that the standard 2000 series cars have considerably greater interior noise level than the 2200 series cars, a result similar to that obtained for elevated structure operation. In both cases the airborne noise is transmitted into the 2000 series cars at higher levels than for the better insulated 2200 series cars. The results also show, however, that the overhauled and modified truck configuration of the 2000 series have about the same interior noise levels as for the 2200 series cars and the modified 2000 series with the soft journal sleeves have considerably lower noise levels than the 2200 series. Both of these latter results are due to lower noise generation at the source; a result that occurred throughout this series of tests both for the wayside noise and the car interior noise, except for operations on the steel elevated structure where it was found that there is little difference in wayside noise which can be attributed to car type or configuration and where the car interior noise is somewhat dependent on car type only.

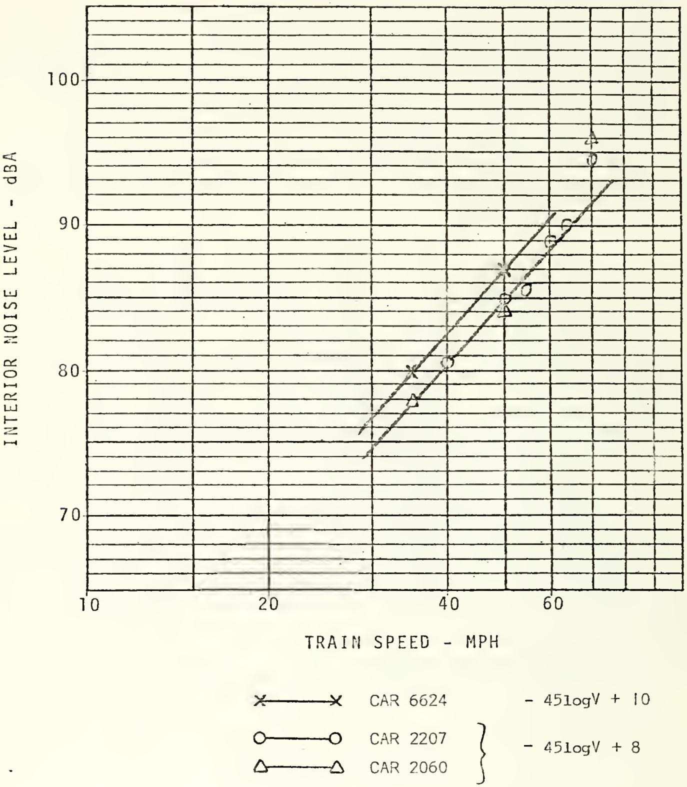


FIGURE 33 CAR INTERIOR AVERAGE NOISE FROM PROPULSION EQUIPMENT WITH WHEELS SPINNING

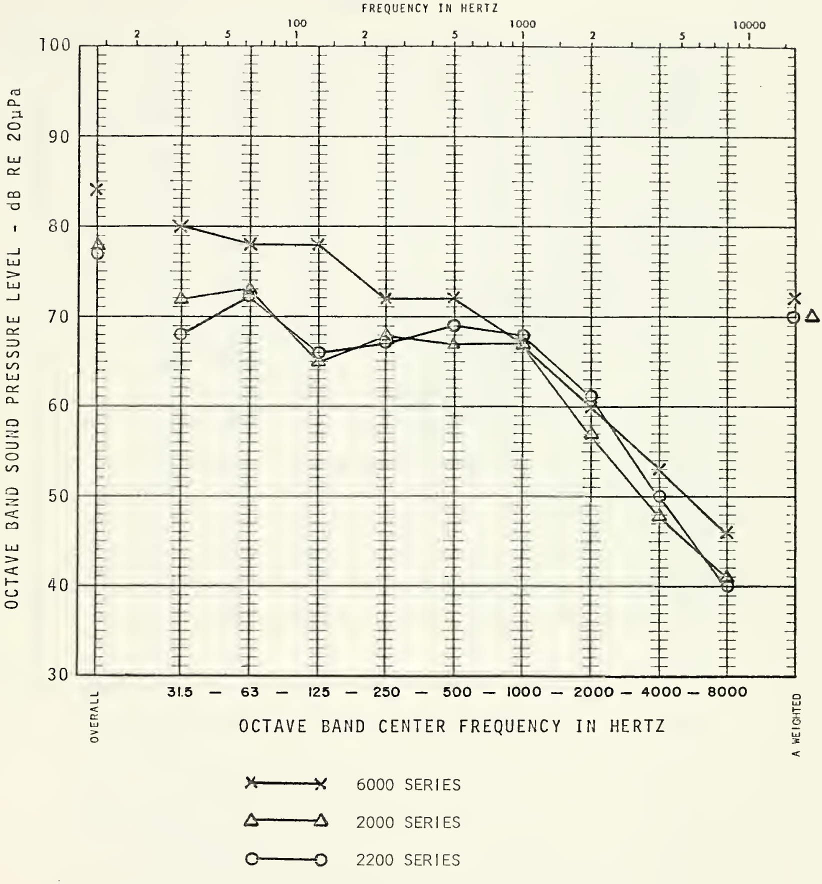


FIGURE 34 CAR INTERIOR AVERAGE NOISE LEVELS DUE TO PROPULSION EQUIPMENT WITH WHEELS SPINNING - NORMALIZED TO 40 MPH SPEED

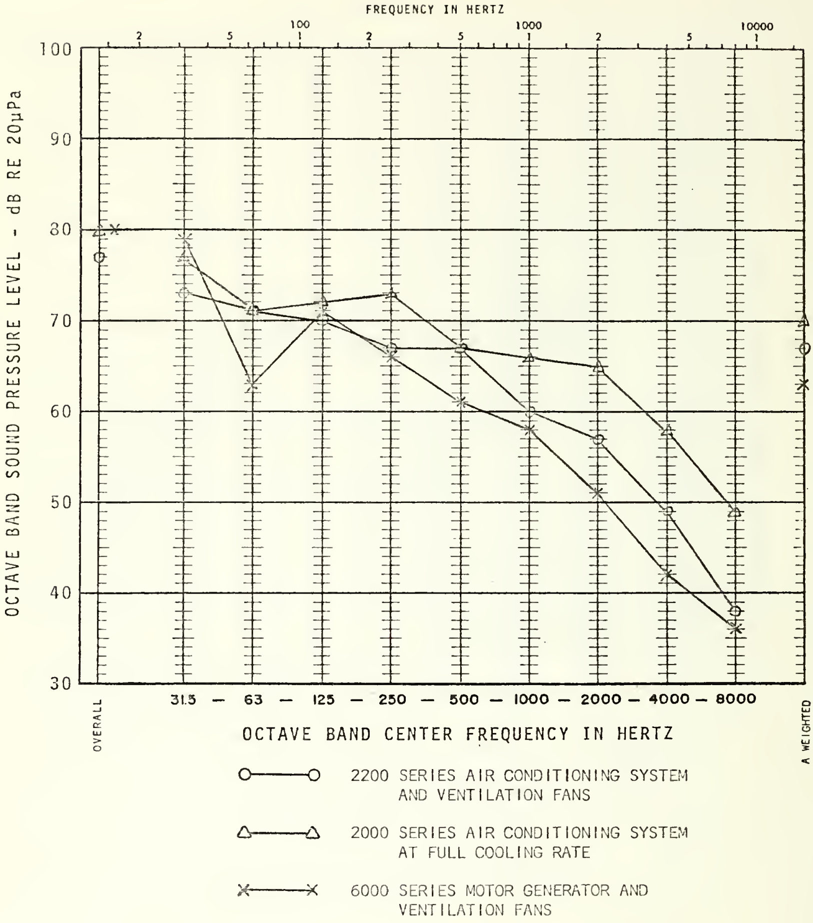


FIGURE 35 CAR INTERIOR AVERAGE NOISE FOR AUXILIARY EQUIPMENT

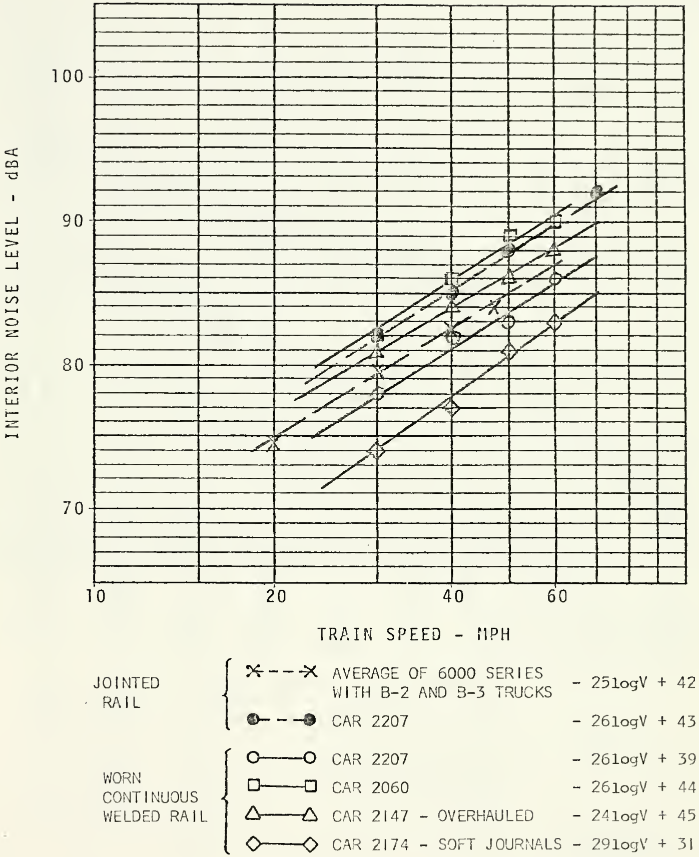


FIGURE 36 CAR INTERIOR AVERAGE NOISE LEVELS FOR OPERATION ON BALLAST AND TIE TRACK - JOINTED RAIL AND WORN CONTINUOUS WELDED RAIL

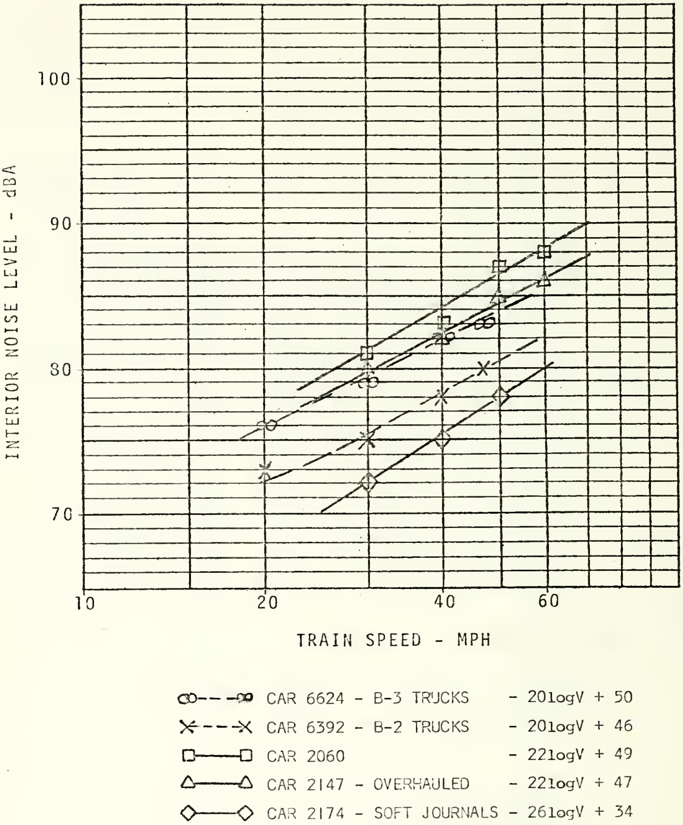


FIGURE 37 CAR INTERIOR AVERAGE NOISE LEVELS FOR OPERATION ON BALLAST AND TIE TRACKS

SMOOTH CONTINUOUS WELDED RAIL

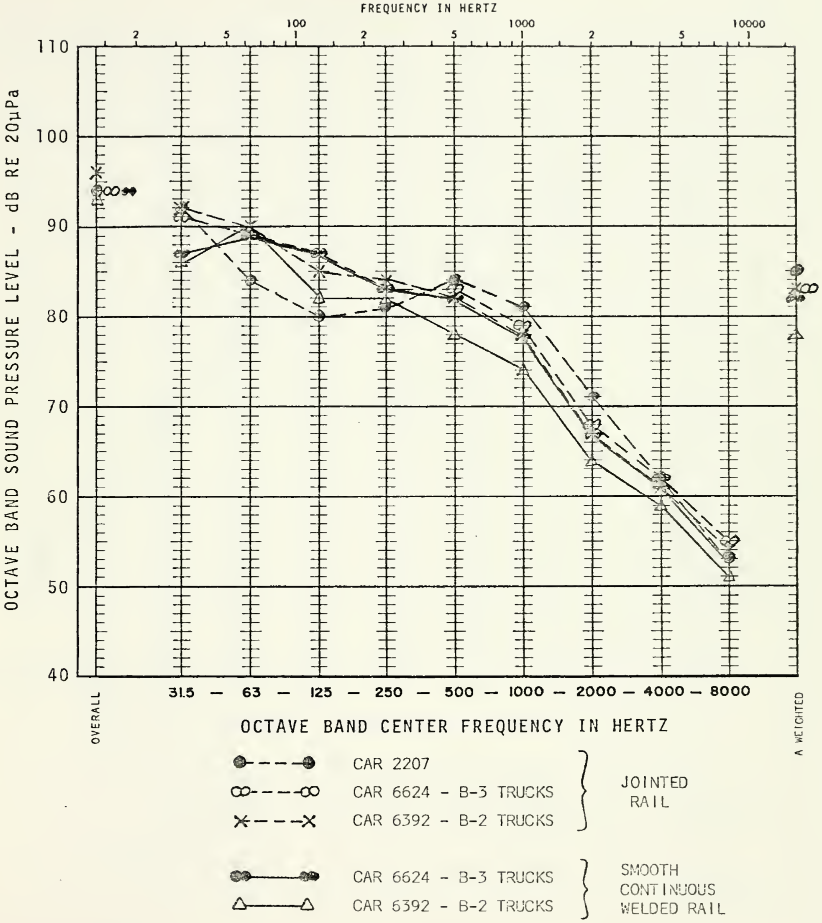


FIGURE 38 CAR INTERIOR AVERAGE NOISE LEVELS FOR OPERATION ON BALLAST AND TIE TRACKS

40 MPH

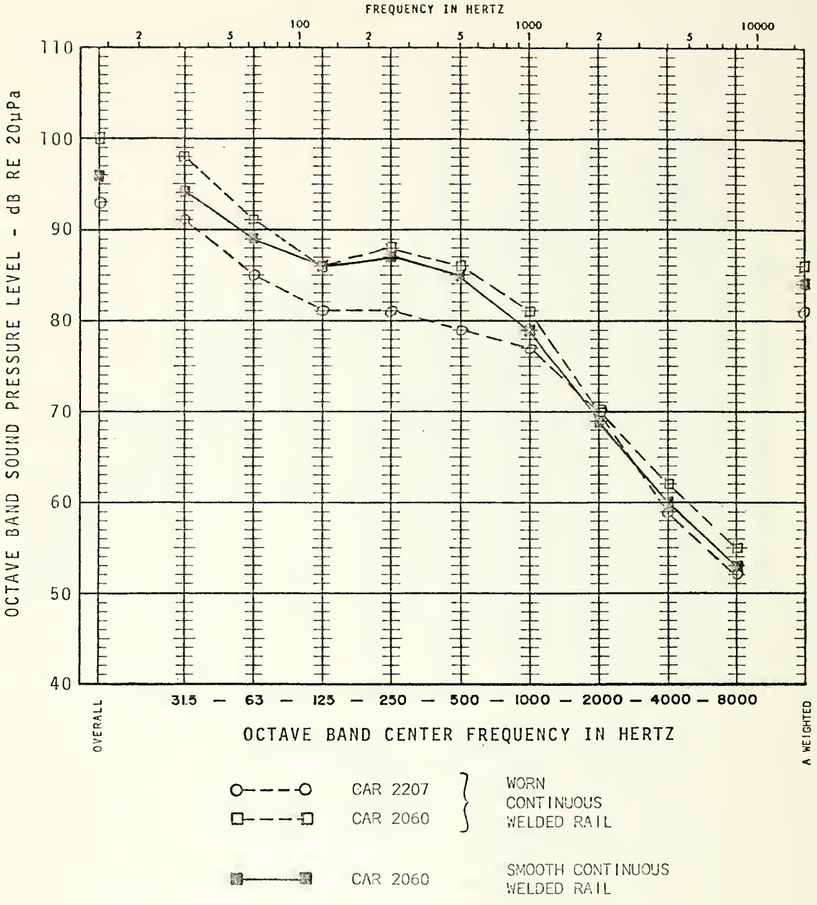


FIGURE 39 CAR INTERIOR AVERAGE NOISE LEVELS FOR OPERATION ON BALLAST AND TIE TRACKS

40 MPH

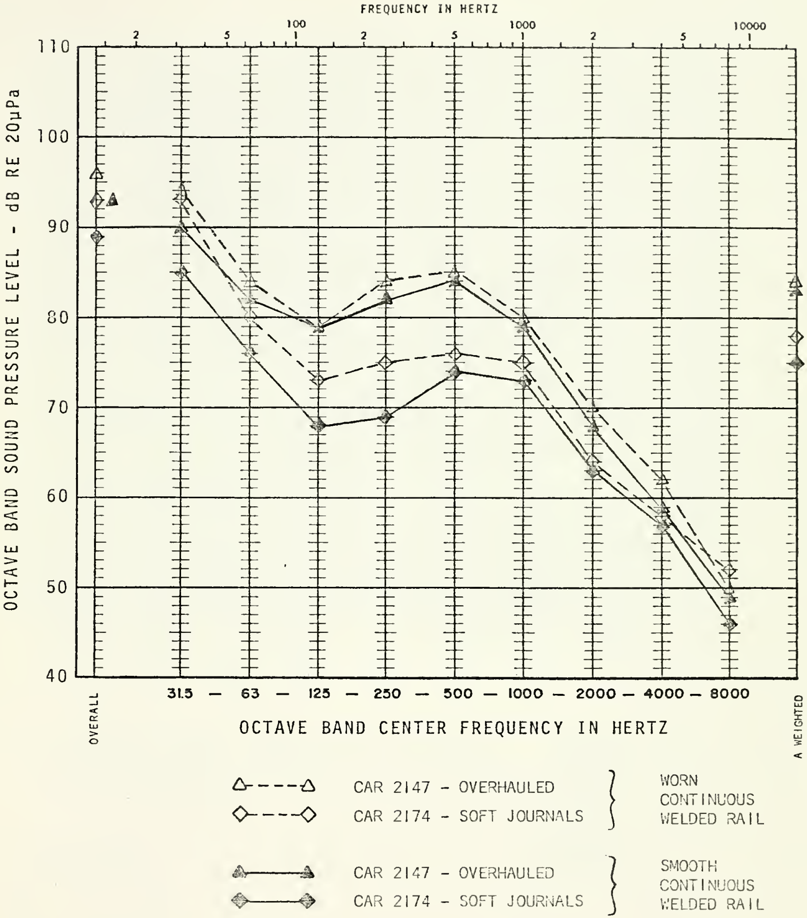


FIGURE 40 CAR INTERIOR AVERAGE NOISE LEVELS FOR OPERATION ON BALLAST AND TIE TRACKS

40 MPH

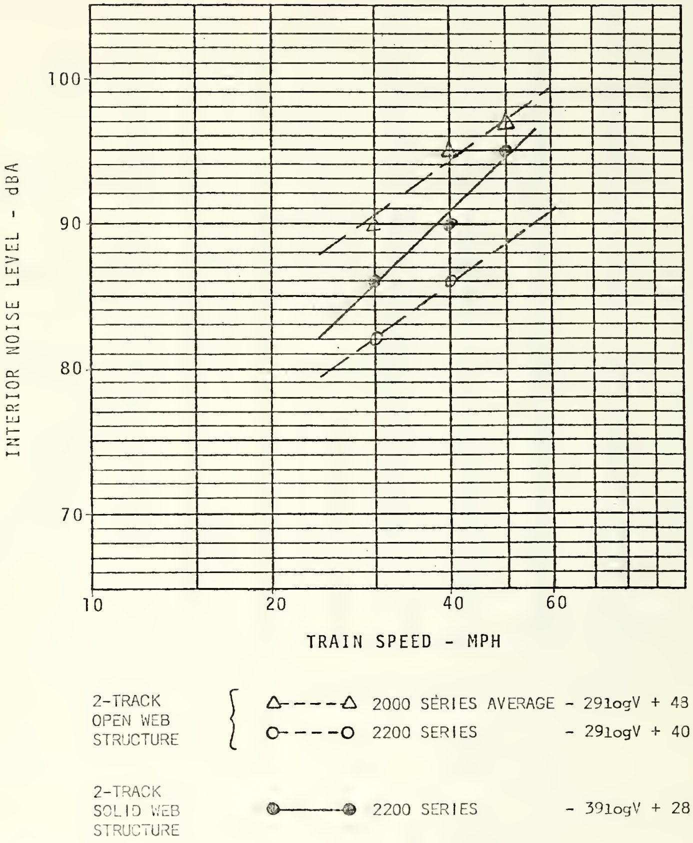


FIGURE 41 CAR INTERIOR AVERAGE NOISE LEVELS FOR OPERATION ON ELEVATED STRUCTURE

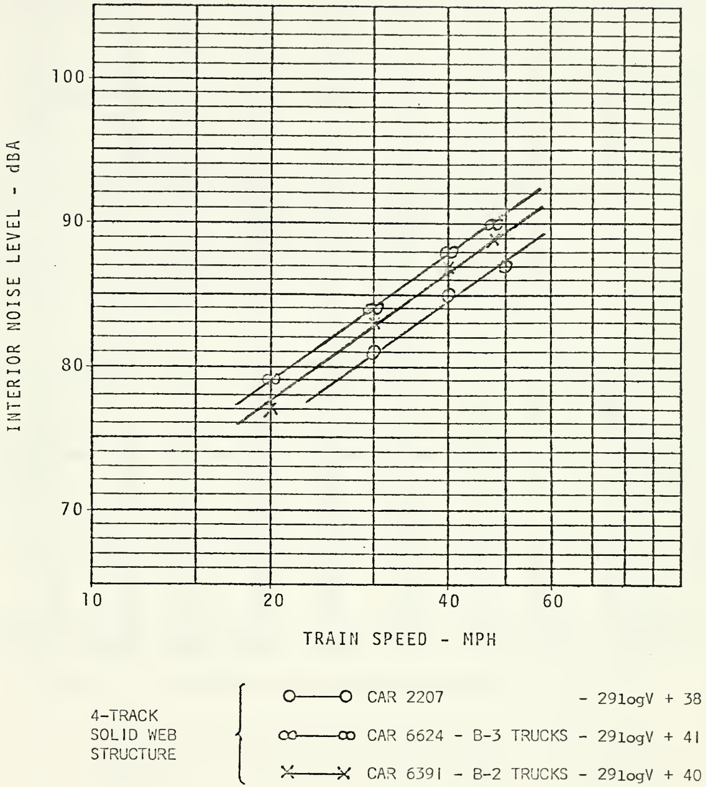


FIGURE 42 CAR INTERIOR AVERAGE NOISE LEVELS FOR OPERATION ON ELEVATED STRUCTURE

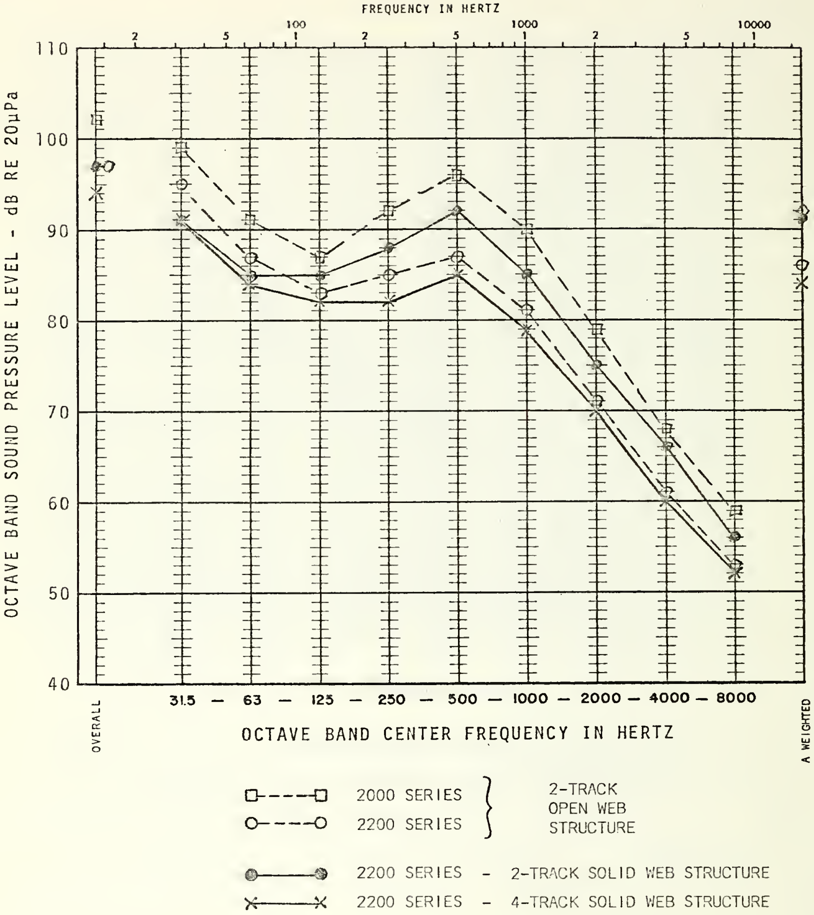


FIGURE 43 CAR INTERIOR AVERAGE NOISE LEVELS FOR OPERATION ON ELEVATED STRUCTURE

40 MPH

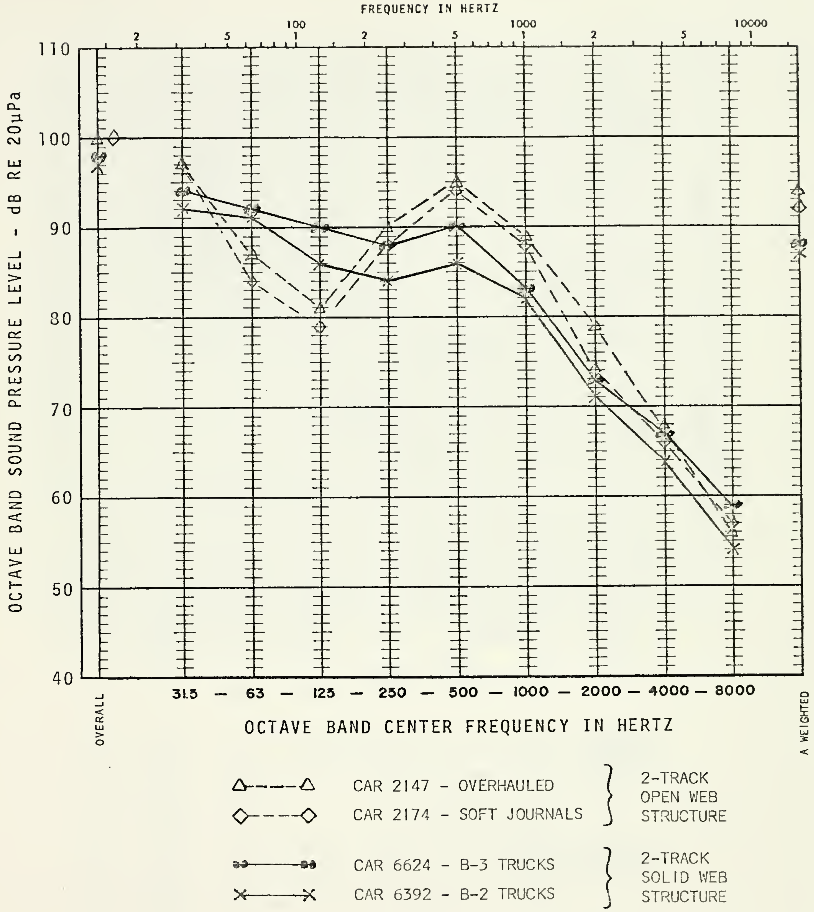


FIGURE 44 CAR INTERIOR AVERAGE NOISE LEVELS FOR OPERATION ON ELEVATED STRUCTURE

40 MPH

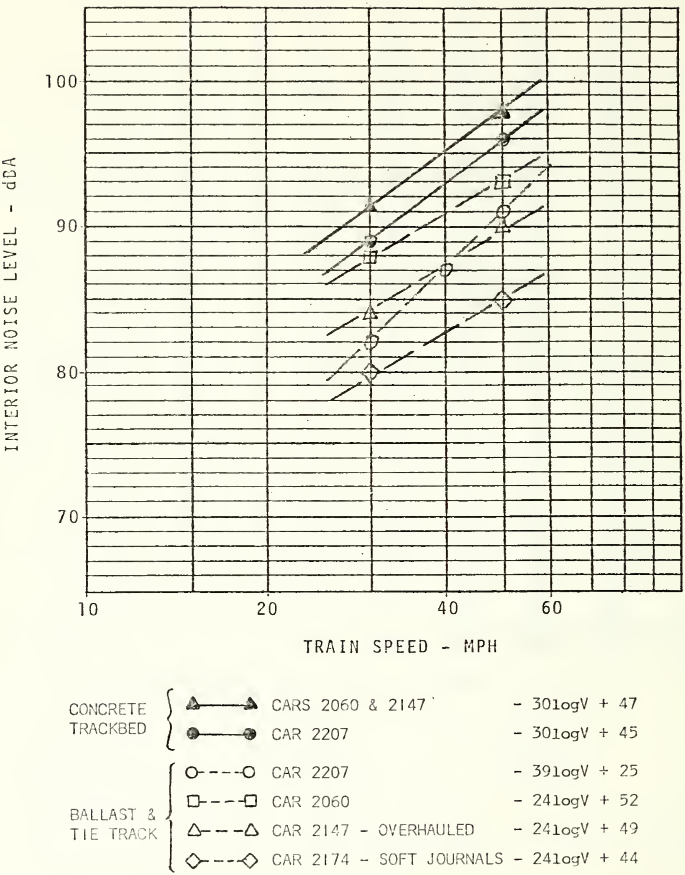


FIGURE 45 CAR INTERIOR AVERAGE NOISE LEVELS FOR OPERATION IN TUNNELS

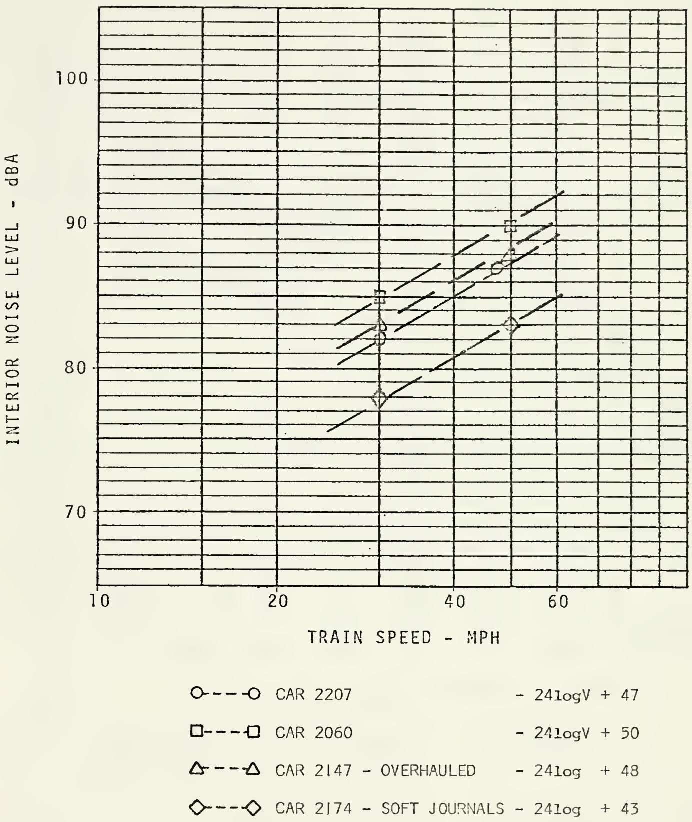


FIGURE 46 CAR INTERIOR AVERAGE NOISE LEVELS FOR OPERATION IN BOX SECTION SUBWAY WITH BALLAST AND TIE TRACK

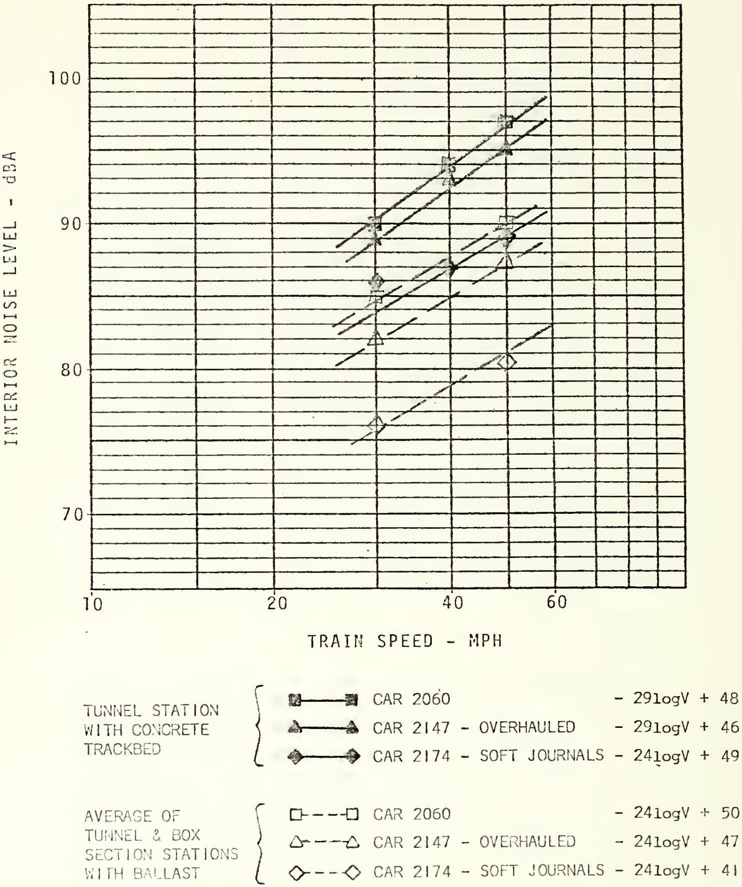


FIGURE 47 CAR INTERIOR AVERAGE NOISE LEVELS FOR OPERATION THROUGH SUBWAY STATIONS

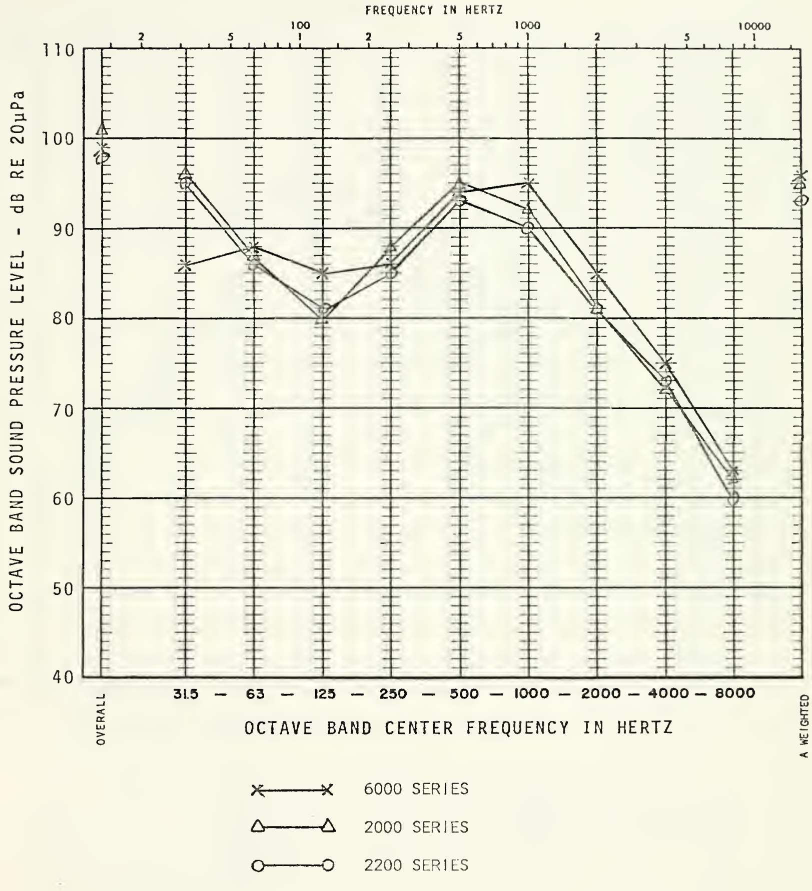


FIGURE 48 CAR INTERIOR AVERAGE NOISE LEVELS FOR OPERATION IN TUNNELS WITH CONCRETE TRACKBED

40 MPH

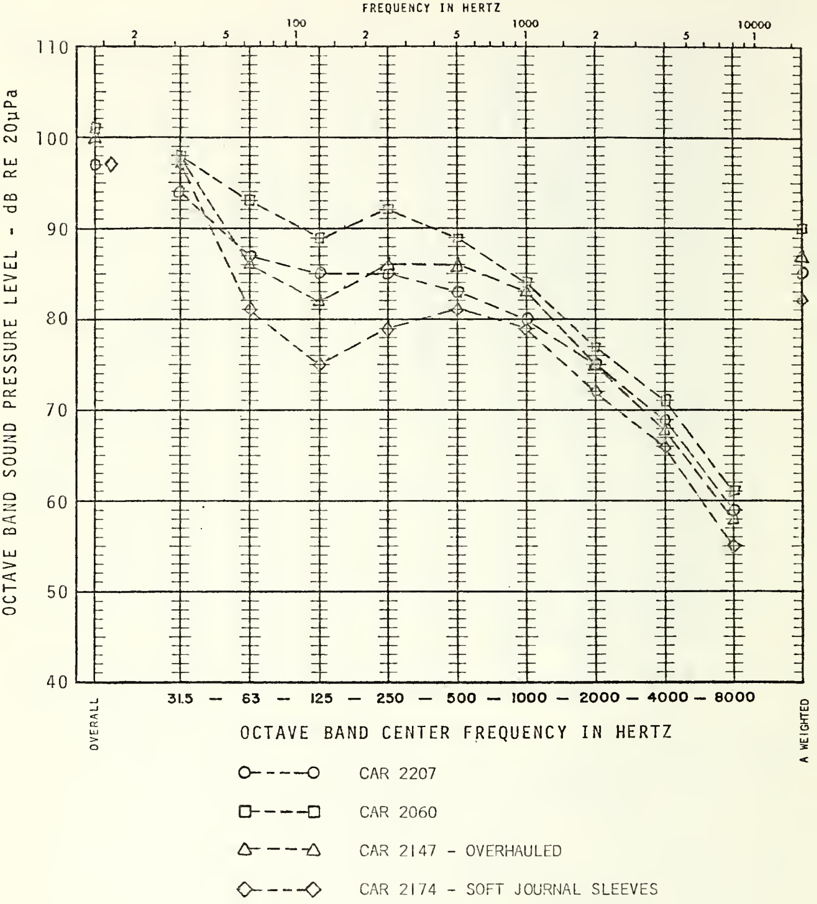


FIGURE 49 CAR INTERIOR NOISE LEVELS FOR OPERATION IN SUBWAYS WITH BALLAST - AVERAGE OF ROUND TUNNEL AND BOX SECTION DATA

40 MPH

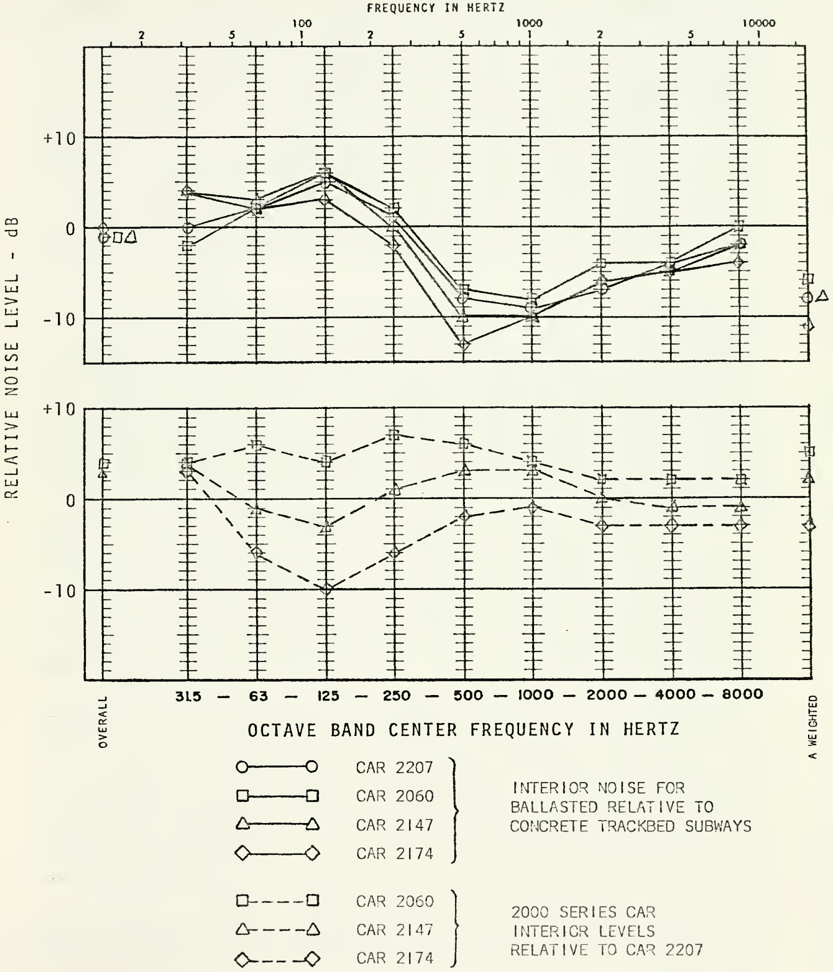


FIGURE 50 RELATIVE CAR INTERIOR NOISE LEVELS SHOWING THE REDUCTION OF NOISE IN BALLASTED SUBWAYS AND COMPARATIVE PERFORMANCE OF DIFFERENT CAR CONFIGURATIONS

IV. CTA VEHICLE AND FACILITY NOISE LEVELS AND POTENTIAL FOR REDUCTION

The results of the noise measurements included in the study show that the noise levels experienced in the CTA transit vehicles, on the subway station platforms and at the wayside cover a wide range of levels. The actual sound levels experienced and the noise exposure of patrons and neighbors is highly dependent on the type and design of the way structure and is somewhat dependent on the type and configuration of the transit cars. One of the basic things that is shown by the comparison of the noise levels for different vehicles and different types of way structures is that there is potential for as much as 15 dBA or, possibly, 20 dBA reduction of the noise levels for those locations and operations where the noise exposure levels are the greatest.

The measurements of the transit vehicle equipment noise, both propulsion noise and auxiliary equipment noise, and the measurements for the vehicle operations on the various way structures show that there is indeed a substantial potential for noise reduction within the basic capabilities of the transit vehicle equipment. That is, for most of the types of operation and facilities the noise levels of the equipment do not contribute significantly to the total noise level and reductions of wheel and rail noise by smoothing the rail and possibly by smoothing the wheels, the reduction of reverberant noise by application of absorption and the reduction of wheel/rail interaction noise by minor modifications to the vehicle trucks can give very substantial reductions of the noise levels.

In terms of noise level magnitude, the highest noise levels experienced by patrons are found at the subway platforms for the round tunnel subway stations with concrete trackbed. On these platforms typical sound levels in the range of 105 to 110 dBA occur both for trains passing through the stations and for trains which stop at the station platforms. Comparison of these sound levels with the sound levels in the subway stations which have sound absorption treatment in the form of ballasted trackbed show a substantially reduced noise exposure level in the stations with the ballast for absorption. It may be assumed by some that the reduced noise level is due to reduced generation of noise at the source. However, the measurements show that most of the reduction can be explained in terms of the absorption provided by the ballast. In fact, the noise power generated at the source is probably very similar in the two types of stations and most of the difference in noise level is due to the sound absorptive effect of the ballast.

The actual measured relative values of the typical station noise levels were 14 to 16 dBA lower noise level in the ballasted track stations compared to the concrete trackbed tunnel stations, see Figure 32. This type of result certainly shows the potential for improved performance in the subway stations without acoustical treatment by application of acoustical absorptive treatment. Also, since the ballasted stations have no acoustical treatment on the walls and ceilings, it is likely that the noise could be even further reduced in these stations through the application of an absorbing material covering at least the ceilings over the platform areas. Such acoustical treatment would have the added benefit of reducing crowd noise and machinery noise by a larger increment than these noises are reduced with just the absorption of the ballast. The added effect of sound absorption treatment on the ceiling in the ballasted track stations would probably result in a total further reduction of the train noise by 2 to 4 dBA and reduction of crowd noise and stationary mechanical equipment noise by 5 to 7 dBA. Noise due to street traffic, which gets into the station through entrances and corridors, would also be reduced by a further 5 to 7 dBA.

It should be noted that the acoustic treatment which has been applied in the stations of the BART system and in some of the stations of the TTC system has been very successful in reducing noise levels. The actual noise levels which occur in the BART system subway stations are about 5 dBA less than in the CTA ballasted track box section stations for operations of trains through the stations at comparable speeds. For the TTC stations the noise levels are comparable to 5 dBA less than that found in the CTA stations with ballasted trackbed.

The net effect of the results discussed above relative to sound absorption treatment in subway stations is that the CTA equipment and stations are such that substantial noise reductions, on the order of 15 dBA, can be achieved by acoustic treatment of the station platform areas. Such a reduction is equivalent to reducing the noise to between 1/3 and 1/4 of the original loudness. Procedures for accomplishing this noise reduction are outlined and discussed in the following section of this report.

The operation of the transit trains in the concrete trackbed running tunnels results in the second highest degree of noise level experienced by patrons of the CTA system. Because the patron exposure to car interior noise is for longer time periods than the exposure on the station platforms this should be considered a noise exposure problem of equivalent or greater level than the platform noise. The results of the car interior noise measurements for operation in the ballasted trackbed subway, compared with the concrete trackbed tunnels show similar effects to those for the station platform noise with sound absorptive trackbed. The car interior noise levels were found to be typically about 8 dBA less in ballasted track subways than in concrete track subways rather than averaging 15 dBA less as on the station platforms.

The results of the noise measurements within the subways, i.e., measurements of the reverberant noise in the running tunnel subways, which are summarized in Figure 29, indicate that the reduction of noise level in the transit cars operating in the subways with ballast is similar to the reduction measured for the reverberant sound outside the cars, compare Figures 50 and 29. Thus, the lower sound levels observed for the transit cars operating in ballasted subway are due to the reduction of the airborne reverberant noise in the subway and similar reductions can be obtained for operations in the running tunnels by application of sound absorbing material on the walls of the subway. As for the station acoustic treatment the following section of this report presents a discussion of procedures and materials to be considered for use in reducing noise in concrete trackbed running tunnels along with a discussion of the results which can be expected.

One of the facility design features that was evaluated by this series of tests was the evaluation of relative noise levels produced by jointed rail, continuous welded rail which is worn and may have corrugations and continuous welded rail which has been smoothed by the rail smoother. The differences in wayside noise for the ballast and tie track operation on jointed rail, worn continuous rail and smooth continuous rail are substantial. The measurement results indicate that changing from jointed rail to continuous welded rail is highly desirable for reducing noise generation but that it is essential to maintain the rail in good smooth condition in order to achieve the potential benefits from the continuous welded rail.

The results of the measurements on jointed rail both for ballast and tie track and the elevated structure, see Figures 15 and 24, show that the noise generation is highly dependent on train velocity, approximately proportional to $V^{3.9}$. Similar measurements for smooth continuous rail show a much lower rate-of-change of noise level with speed with the dependence approximately proportional to $V^{2.9}$. For the rough or worn continuous rail the noise generation characteristic was intermediate between these two, being approximately proportional to $V^{3.5}$. It is apparent from the results that the roar noise characteristic of operation on smooth welded rail is much less dependent on speed than the impact noise which is a characteristic part of the wheel/rail noise from operation on jointed rail and which apparently contributes to the total noise from operation on rough continuous rail.

The main features that are shown by comparing the results of the various measurements of this series are that obtaining the full potential from other characteristics, either of the vehicles or facilities, which contribute to low noise operation requires smooth continuous welded rail. When the rail is rough or jointed the differences between the vehicle performance levels are less and, in fact, with the jointed rail [on both ballast and tie track and elevated structure] there was very little difference in the wayside noise for operations of all of the types of cars and all configurations of each type. There are still some differences in interior noise, however, these were largely associated with car body sound insulation characteristics and not with the noise generation characteristics of the car and structure configuration. It is apparent from this information, and from similar information developed on other transit facilities, that smoothing of continuous welded rail is essential to obtain the full potential for low noise operation of the transit system. There is some information available which indicates that grinding of the jointed rail will give significant or substantial noise reduction, however, this is one factor which should be further investigated since there is no definite data available.

Comparison of the results of two basic types of elevated structure, the solid web structure and the open web structure, shows that there is no significant difference in the noise generation which can be attributed definitely to the type of structure. Although one set of data showed a much higher noise level for the solid web structure, another set of data for similar conditions showed comparable or lower noise levels for the solid web structure than for the open web structure. The indication is that the rail condition has a much stronger effect on the noise level than does the structure type. This particular series of tests thus tends to indicate that rail grinding on the jointed rail can reduce the noise level inside the cars and probably at the wayside. However, it is probable that the wayside noise level for the section of solid web elevated structure that gave higher sound levels in the cars would also have given higher sound levels at the wayside than shown on Figures 24, 25 and 26. Therefore, it is still not certain that rail grinding on the elevated structure would reduce the noise levels to be below the values shown on Figure 24 for exterior noise and on Figures 41 and 42 for the car interior noise.

One of the most significant comparisons that is shown by the data developed during this study is the difference in noise generation characteristics of the different configurations of 2000 series cars and the differing performance of the different types of cars in terms of both car interior noise levels and wayside noise levels. One of the types of comparisons included in the tests were several series of measurements for the same conditions using 6000 series cars with B-3 trucks and 6000 series cars with B-2 trucks. In general terms, it was found that there is no signficant difference in the noise levels either wayside or interior, for these two configurations of 6000 series cars. It was found, however, that there is a characteristic difference for the frequency range included in the 125 and 250 Hz octave bands. For this range of frequencies the 6000 series cars with B-2 trucks consistently show lower noise levels, both in the wayside noise level for operation on ballast and tie track and for car interior noise levels. For those tests which showed measurable difference in the noise level for the cars equipped with B-3 trucks and those with B-2 trucks, it was found that the cars with the B-3 trucks were quieter by 1 to 2 dBA. This difference, however, is not very significant and the only consistent result was the lower noise levels for the low frequency range included in the 125 and 250 Hz octaves.

With regard to differences in the car noise performances, one of the results found was that the 2200 series car bodies are significantly better insulated against transmission of airborne noise from beneath and around the car to the car interior. The 2200 series cars have lower interior noise levels for identical operating conditions than the standard 2000 series cars, for those way structures where differences were observed. The 6000 series cars were slightly noisier than the 2200 series and are intermediate between the 2200 and 2000 series cars for interior noise.

Considering comparisons of car performance, it was found that by modification of the 2000 series cars a considerably reduced noise level both in the car and to the wayside can be achieved. The modifications applied to the 2000 series car trucks during overhaul result in somewhat lower noise levels both at the wayside and in the cars. Some of this reduction could have been due to better condition of the wheels at the time of the tests. Smooth wheels could be part of the reason why the difference was less apparent on jointed rail or rough rail because the effect of smoother wheels would be less with the rougher rail. However, considering only the results of the tests, it does appear that substantial noise reduction for the 2000 series cars does result from the overhaul procedure. The net result is to reduce the noise to similar levels to those found for the 2200 series cars for interior noise and for wayside noise on ballast and tie track.

A further modification of the 2000 series cars, consisting of using very soft rubber journal sleeves between the axles and truck frames, did result in further substantial reduction of both wayside and in-car noise for every type of operation except for running on ballast and tie jointed rail and elevated structure with jointed rail. This reduction in the stiffness of the bearing sleeves at the axles results in effectively reducing the unsprung weight at the wheels while, at the same time, providing better vibration isolation between the wheels/axles and the truck frames. The net effect is better vibration isolation between the wheels and the car bodies. The overall result was a reduction of 3 to 5 dBA in wayside noise and up to 8 or 9 dB in car interior noise for some operating conditions, a substantial reduction achieved by a relatively minor modification of the vehicles.

Achieving the maximum effectiveness from the change in the 2000 series suspension system does require coordination with other factors which result in reduced noise. For example, the maximum effectiveness was found for operation in subways with ballast and tie track on relatively smooth continuous welded rail. Thus, the combination of soft journal sleeves, sound absorption in the subway and smooth continuous welded rail resulted in the greatest overall improvement in performance when comparing the results from different cars. An alternate way of stating this is that achieving the full potential for noise reduction from the modification of the transit vehicle suspension system requires the presence of other facility features which result in reduced noise. Combining all of these factors results in overall reductions which are very significant. For example, for operation in the subways with concrete trackbed the interior noise in the cars with the soft journals was only 2 to 3 dBA less than for the standard 2000 series car. However, in the subways with ballast and tie track the car with the soft journal sleeves had 7 dBA less interior noise than the standard 2000 series car. Further, the car interior noise on the modified 2000 series cars with the soft journal sleeves was quieter than the 2200 series cars by 4 to 5 dBA for most conditions in the subways with the ballast and tie track.

The main point of these observations is that the experiments and measurements have shown that it is certainly possible to decrease the patron noise exposure in the cars through minor but significant modifications to the truck suspensions without the need for modifications of the car bodies such as increase in the sound insulation, a procedure that would be costly and would undoubtedly increase the weight of the transit cars. The modification to the journal sleeves, which gives substantial noise reduction and improved ride quality, is a change that does not affect the operational characteristics of the car and does not affect the weight, but probably will increase the life of the truck components due to reduced vibration and shock levels transmitted to the truck frames.

V. PROCEDURES FOR REDUCTION OF NOISE

The results of this study of the CTA transit train noise indicate that it is possible through maintenance procedures and modifications to achieve significant reduction of the patron noise exposure and reduction of the wayside noise levels for the CTA transit train operations. The most effective procedures available for reduction of the noise are application of sound absorbing material in the subways for absorption of sound in reverberant subways, smoothing of the rail by grinding procedures to reduce the level of the noise at the source and modification of the transit cars to reduce the noise generation at the source. The transit car modifications evaluated were associated with softening of the springing to reduce the effective unsprung weight at the wheels and provide better vibration isolation between the wheels/axles and the transit car bodies. A procedure not evaluated is modification of the car wheels using either damped or resilient wheels. Resilient wheels are effective in reduction of wheel squeal noise, are especially effective in reduction of wheel squeal noise, a noise which results in high noise levels experienced both by patrons and wayside neighbors.

The following discussions indicate recommended procedures for reduction of noise to consider for application in those areas where the noise level is greatest and, therefore, reduction will be of greatest benefit to CTA patrons.

A. Rail Smoothing

It has long been recognized that smoothing of the rail with a grinding technique which results in reduced roughness of the rail gives reduced noise generation. For this series of tests the only direct comparisons made of the effects of rail grinding were for the series of tests on ballast and tie track. These results showed a substantial noise reduction. See, for example, Figure 19, which shows the comparison between jointed rail, worn continuous welded rail and smooth continuous welded rail. In this case, for the configurations of cars tested, the rail smoothing resulted in 4 to 6 dBA reduction of the wayside noise, considering only the difference between the worn continuous welded rail with corrugations and the rail after smoothing with the rail smoother. Less reduction was obtained for the car interior noise, however, there was a significant reduction of noise.

The series of tests in the smooth bore subways with concrete trackbed showed very high sound level with very little difference between types of cars. A contributing factor to this result was probably the fact that the rail was rough and corrugated at the time of the test. With rail smoothing the noise would be less with larger differences between the different configurations of cars. At times when the rail in the subways has been smoothed, reductions in noise level of 6 to 9 dBA and sometimes greater have been reported.

Since the CTA does experience corrugations and roughening of the rail, it is essential for minimizing noise generated by the train operations that the rail be ground periodically and maintained in smooth condition. The results of the tests show that it is necessary to have smooth continuous welded rail in order to obtain full advantage of other design features or characteristics of the facilities and vehicles which contribute to low noise operation.

Although it has been known and demonstrated, on many occasions, that grinding of the rail does produce noise reduction, this series of test results show that not only does rail smoothing produce noise reduction but that it changes the speed dependence of the noise and that the amount of noise reduction obtained is different for different types of cars. In this latter regard, for this series of tests some of the difference could have been due to wheel condition. However, the results do show that with smooth rail the quieter operating cars give even greater noise reduction when comparing operations on rough continuous rail with smooth continuous rail.

In general, the measurement results show that the wayside noise for jointed rail was proportional to $V^{3.9}$, for rough continuous rail the noise was proportional to $V^{3.6}$ and for smooth continuous rail the noise was proportional to $V^{2.9}$. Thus, the use of smooth continuous rail not only results in lower noise but in a reduced rate of increase of noise with speed permitting higher speed operation for a specific level of noise radiation.

It has not been determined definitely, at the time of this writing, whether or not smoothing of jointed rail can provide, any significant noise reduction. Some tests performed at the NYCTA facilities indicate that grinding of jointed rail does not improve the noise. The jointed rail tests for this series of measurements both on ballast and tie track and elevated structure show that the noise is proportional to $V^{3.9}$. This implies that a major part of the noise is due to impact at the joints since the roar noise for smooth rail is proportional to about $V^{2.9}$. For interior noise similar results are obtained with the noise on jointed or rough rail being proportional to $V^{2.6}$ and for smooth continuous rail being proportional to $V^{2.2}$, i.e., greater dependence on speed for jointed rail than for smooth continuous welded rail.

It is possible that smoothing of the jointed rail will result in some noise reduction, however, there will still undoubtedly be some impact noise due to the presence of joints even when they are well aligned and smoothed by grinding. The joints do flex when they are loaded with the transit car wheels and this flexure, particularly on the relatively flexible elevated structure, may prevent obtaining significant benefit from smoothing of the jointed rail. Changing from jointed rail to continuous welded rail on the elevated structure would result in reduction of the wayside noise and car interior noise for operations on the elevated structure. For this kind of change it is expected that at least 8 to 10 dBA reduction of wayside noise and car interior noise would be obtained.

B. Wheel Squeal Noise

While not included specifically in the measurements and results of this study, the general principles for reduction of wheel squeal noise have been developed in other studies and, therefore, some comments can be made. There are two general procedures for reducing wheel squeal noise; [1] lubrication of the rail and [2] damping of the car wheels. Of these two, damping of the car wheels is desirable because it does not create maintenance problems with the rail, however, it is expensive in terms of wheel modification or acquisition costs.

Two types of damping are available for reducing wheel squeal noise; [1] viscous or ring dampers applied to the solid wheels and [2] the use of resilient wheels. Either of these procedures will give substantial reduction of the wheel squeal noise for operations on all types of track structure and for both car interior and wayside noise. If such procedures are contemplated for reducing the wheel squeal noise it is recommended that the resilient wheel concept be given strong consideration because resilient wheels not only reduce wheel squeal on short radius curves but they also can result in significant reduction of roar noise in subway operations with some accompanying reduction of car interior noise. Damped wheels may also contribute to reduction of roar noise although not to the extent expected with resilient wheels.

C. Running Tunnel Acoustic Treatment

One operation where patrons are exposed to the greatest noise levels, for the longest time periods, is running in the smooth bore concrete trackbed tunnels. Therefore, it is appropriate to consider acoustic absorption treatment for reduction of the roar noise in the subways. As shown by the series of measurements reported herein, the use of absorption in the subways can result in substantial reduction, on the order of 8 to 10 dBA reduction, for car interior noise in the running tunnels with concrete trackbed.

To obtain further improvement after rail smoothing, the best procedure for reducing the noise in the smooth bore tunnels with concrete trackbed is the application of sound absorbing material to the tunnel walls. The three basic factors to be considered in the design of running tunnel sound absorption are: [1] the location for placement of the material; [2] the type of material to be used and; [3] the extent or coverage of the material.

As discussed in the section giving the results of the measurements and as presented in the following subsection on station acoustic treatment, the most effective location for the material is the lower part of the side walls. Application of sound absorbing material at these locations can accomplish both the reduction of reverberation in the subway and, because all the noise sources on a transit vehicle are in the space beneath the car, such locations for the sound absorption minimize the reflection of sound and, therefore, optimize the efficiency of the sound absorption material in reducing noise. Placing the sound absorbing material on the trackbed presents problems of maintenance and durability and, therefore, the recommended location for the sound absorbing material is the side walls - concentrating on the lower side walls.

The requirements for fire resistance, mechanical durability and cleanability of the sound absorption material to be used in tunnels place considerable limitations on the choice of materials, however, there are a number of types of materials which have satisfactory properties. One type of material recommended for consideration for use in the tunnels is spray-on mineral fiber applied at a thickness of 1" ± 1/4". This form of material has been demonstrated to give adequate fire resistance, durability and cleanability in existing subway installations and the sound absorption data, calculations and results with existing installations indicate that good noise reduction can be obtained. The second type of material to be considered is the fiberglass blanket with a waterproof or impervious covering and expanded metal or hardware cloth cover for mechanical protection. Either of these types of materials will give satisfactory results. With the fiberglass material, since the absorption coefficients are greater, the area of coverage can be somewhat less.

The extent of area of coverage in application of the sound absorbing material depends on the degree of noise reduction desired and the extent to which noise reduction is to be provided in the subway system. There are some practical limitations on the maximum amount of noise reduction which can be obtained by the use of sound absorption treatment. Estimates of the noise reduction as a function of total area of coverage or percentage of area of coverage on the walls indicate that there are some optimum ranges of coverage extent which give the maximum return in terms of noise reduction per sq ft of material installed.

For the treatment of the CTA round tunnels or horseshoe tunnels with concrete trackbed, the recommendation is the application of a spray-on material continuously along both sides of the tunnels for a height of 8 to 10 ft, starting from the invert or walkway and extending up the side walls. If the application is to be of fiberglass with mechanical attachment a width of treatment of 5 to 6 ft should be sufficient using a 1" or 1-1/2" fiberglass blanket of 2 to 6 lbs/cu ft density. Such treatments should be sufficient to result in 6 to 8 dBA reduction of the car interior noise level.

There are many types of spray-on materials which are marketed as sound absorption materials. Some of the products are effective as sound absorbing materials and some are very ineffective. The special requirements of the tunnel installation for reasonable mechanical durability, fire resistance, and the ability to withstand waterspray for cleaning limits the selection of materials even further. None of the materials described as "acoustic plaster" provide satisfactory sound absorption or mechanical properties and, therefore, should not be considered. Some of the materials are mineral fiber and some are cellulose fiber. Because the cellulose fiber materials do not retain their chemical fireproofing treatment [particularly when washed] they should not be considered.

The following list indicates those mineral fiber materials which have been demonstrated to have the necessary properties and which should be considered.

TABLE XIV List of Spray-On Acoustical Absorption Materials to be Considered for Use in Running Tunnels

Product	Type and Typical Thickness	Manufacturer or Supplier
Pyrok	3/4" to 1-1/4"	Pyrok Ltd., Somerset, England
Sound Shield "85"	1/2" to 5/8" Mineral Fiber	United States Mineral Products Company
Kilnoise	1/2" to 5/8" Mineral Fiber	Tiger Brands, Inc.
Pyrospray	3/4" to 1" Mineral Fiber	Keene Corporation [Baldwin-Ehret-Hill, Inc.]
Edmar	1" Mineral Fiber	Edmar Technical Systems, Inc.

Pyrok, Sound Shield "85" and Kilnoise have all been found by the TTC to be acceptable under the requirements of their specifications. The TTC specifications require an NRC of 0.50 minimum and indicate that sound absorption material installed on the side walls is to be subjected to semi-annual washing. The washing consists of two passes of a wall washing machine first with a spray of mild detergent and second with rinse spray. The water pressure at the pump is 500 lbs/sq in, the spray nozzle capacity is .94 gpm and the nozzle is 10" from the material with a spray angle of 57°. The nozzle apparently produces a relatively fine spray so that there is not a great deal of force applied to the sound absorption material by the water spray, however, the TTC, to this date, has approved only three materials as being adequate to provide the specified sound absorption and have adequate durability and cleanability or resistance to water spray. Thus, the background and experience at the TTC indicates that the first three materials on the list are satisfactory products with adequate durability for use in subway structures.

The WMATA Metro system is making extensive use of Pyrok applications 1" thick for running tunnel and fan and vent shaft treatment. This material is cementitious, using vermiculite filler, and is very durable and fireproof. The WMATA installations, however, have given poor results, apparently because of the application technique used.

It is very important to remember in the installation of any spray-on material that the concrete must be thoroughly cleaned of any dirt, residue, oil or other film that may be on the concrete. Any residue or oil can result in poor attachment or release of the spray-on acoustical material. Thus, the application procedure must include cleaning of the concrete before spraying to be sure that the installation will be durable. Apparently the cleaning was not adequate in the WMATA subways because some of the material has fallen off the walls. Other installations have not experienced this problem.

The following section on subway station platform area noise reduction treatment presents discussion of fiberglass absorption materials, the materials which can be used for wrapping and waterproofing the fiberglass and the materials which can be used for mechanical retention. With a fiberglass panel system it would be possible to install sound absorption panels in the running tunnels during revenue service times because the panels could be brought in as prefabricated sections and attached to the subway walls using powder actuated studs or ramsets. The installation of the spray-on material is a more difficult process which would require access for longer periods of time in the subway.

D. Subway Station Platform Area Noise Reduction

Considerable reduction of patron noise exposure can be achieved in the subway station platform areas with the relatively simple, although not necessarily inexpensive, addition of sound absorption treatment. The costs of such modifications depend considerably on the architectural requirements or architectural appearance required of the sound reducing treatment applied.

The sound level measurements made in the existing CTA subway stations, as given in Appendix D and discussed on Pages 51 to 57 of this report, show that application of sound absorbing treatment in the stations, in the form of ballasted trackbed, provides for substantial reduction of the train noise compared to that experienced in tunnel stations with concrete trackbed. Analysis of the results of the measurements shows that most of the reduction can be accounted to the sound absorptive effect of the ballast. Thus, it is apparent that the intense noise in the tunnel stations with concrete trackbed could be reduced at least to levels comparable to those experienced in the box section stations with ballast by the addition of sound absorption materials applied to the existing surfaces of the subway station platform areas.

The data given on Table VII and on Figures 30, 31 and 32 show that the noise levels in the stations with absorptive ballasted trackbed are about 15 dBA less than for comparable operations in the round tunnel stations with concrete trackbed. This is a substantial reduction of the noise and gives the subjective effect of reducing the noise to be between 1/3 and 1/4 of its original loudness. Because of the very high intensity of the noise levels which occur on the platforms in the tunnel stations, 100 to 110 dBA, and because of the large number of patrons exposed to these noise levels in the many tunnel stations, the reduction of the tunnel platform noise would result in substantial reduction of the total patron noise exposure.

It should also be mentioned that similar results have been achieved at the Toronto Transit Commission facilities. Compared with untreated stations, noise level reductions of 10-13 dBA were achieved in TTC tunnel station platform areas with sound absorption material applied to the ceilings and underplatform overhang surfaces. No direct comparisions of treated and untreated platforms are available for the BART stations because all the BART subway platform areas have acoustic absorption treatment. The effectiveness can be inferred from the fact that the train noise on BART subway station platforms is well controlled and the levels are lower than for the CTA platforms with ballasted track for similar operations, i.e., passbys of trains at constant speed.

The basic procedure for reducing noise in subway station platform areas is the application of sound absorption material for reducing the reflection and reverberation of sound in the space. Two factors are important in the design of the sound absorption treatment; [1] the total area or amount of the sound absorption and [2] the placement of the absorption material. The amount of sound absorption material determines the amount of reduction of the reverberation time of the space. The reverberation time is a measure of the persistence of sound in an enclosure and is an indication of the rate of absorption of sound energy. The sound level from a given noise source is reduced in proportion to the total amount of sound absorption present in the space and is, therefore, proportional to the reduction in reverberation time. Where the spaces are of different size the same amount of absorption will give less reduction of reverberation time in the larger space but will give similar total noise reduction.

The data in Table VIII, indicating the measured reverberation times in the subway stations, show that the ballasted trackbed, which contributes about the same total amount of absorption in the tunnel stations and the box section stations, reduces the reverberation time to a shorter value in the tunnel station than for the box section station. The cross-sectional area and the total volume of the tunnel stations are less than for the box section station so that the net reverberation time is longer in the box section station. The total noise reduction is about the same for the two configurations because the total absorption applied is about the same.

The measurements in the various CTA subway stations, the calculations relative to the acoustic properties and amount of sound absorption needed for noise reduction and the comparison with results achieved in the acoustically treated BART and TTC subway stations have provided a basis for deriving recommended noise reducing acoustic treatment configurations for the CTA tunnel station platform areas. The reverberation measurements in the tunnel stations with concrete trackbed provide a basis for calculating the natural absorption of the platform room surfaces.

Table VIII indicates the results which were obtained by measurements made in the various station platform areas. The measurements in the tunnel stations with concrete trackbed did indicate a relatively short reverberation time, considering that the spaces have no sound absorption treatment present. Measurements in other spaces which are of all concrete and steel construction and of similar volume, but without columns or the relatively complex shape of the CTA round tunnel stations, indicate reverberation times in the range of 8-12 seconds for the 250 to 500 Hz frequency range. Apparently the presence of the columns and the relatively complex shape, [islands on the platform, arched ceilings, etc.] result in sufficient sound diffusion that sound energy is absorbed at a higher rate than normally expected for a space which is completely untreated. This result tends to indicate and confirm that application of sound absorption material to the stations will give substantial noise reduction.

To determine the appropriate acoustical treatment to be applied to the tunnel stations, calculations have been done to determine the natural absorption present due to the interior surface materials and configuration and to determine the added absorption necessary to give certain degrees of noise reduction. In general terms, it was found that the minimum recommended acoustical treatment to be added to the stations is 14 sabins per linear foot and the desirable treatment is 25 sabins per linear foot of platform. The sabin is the unit of sound absorption, equivalent to square foot units, obtained by multiplying the area of an absorption material in square feet by the dimensionless sound energy absorption coefficient [which is always somewhat less than 1.0]. Taking into account the size of the CTA tunnel stations, for optimum results the reverberation time of the platform areas should be reduced to the range of 1.0 to 1.4 seconds for the mid-frequency range.

1. Placement of Materials

One of the factors which should be considered in deriving the optimum location for sound absorbing material in platform areas is the effect of reflective surfaces compared to absorptive surfaces on the amount of sound energy fed to a reverberant space by a sound source, as discussed on Pages 48 through 57. In general, only a portion of the sound energy produced by a source contributes to the reverberant sound in an enclosed space and that portion is the amount of sound energy left in the sound waves after the first reflection from a surface. When the surfaces are highly reflective, the amount of sound energy contributed to the reverberant sound is nearly the total energy radiated by the sound source. When the first surface, encountered by a sound wave as it propagates away from the source, is highly absorbent, then the amount of sound energy fed to the reverberant field is reduced. For example, when the first surface that a sound wave strikes absorbs 50% of the sound energy, i.e., reflects only 50% of the amount of contributed energy when the first surface encountered is highly reflective.

For subway platforms, because of the physical arrangement and because the main noise source is the transit trains with all the noise sources in the confined space beneath the transit cars, sound absorption materials on the walls near the undercar space can be used to efficiently reduce noise by absorbing sound energy near the source to reduce the amount of sound energy fed to the reverberant sound field and by reducing the sound transmitted along the platform in addition to the normal reduction obtained by reducing the reverberant build-up of sound level. In placing sound absorption materials in a subway station then, the most effective and efficient location is on the trackbed beneath the transit trains and at each side of the transit cars along the vertical or near-vertical walls beneath the platform level, including the bottom of the platform overhang ledge, if any significant area is available. The next most effective location is on the tunnel side wall opposite the platform and the third most effective location is on the platform and/or tunnel ceilings.

In general it has been found that efforts to place sound absorption material on top of a concrete trackbed have been unsuccessful. The material tends to become clogged with dirt and presents a maintenance problem. While it is effective when new, it deteriorates rapidly and becomes an ineffective treatment. Therefore, in practical terms the most effective and efficient placement location for sound absorption treatment is on the underplatform vertical surfaces and on the lower portion of the tunnel wall opposite the platform. In fact, it is essential that there be sound absorption material on the underplatform surfaces in order for the overall sound absorption material application to work effectively in reducing the platform noise.

Figure 51 presents data obtained on station platforms at the BART system for two stations which have extensive ceiling acoustical absorption and comparable, short reverberation times. However, one station lacks underplatform sound absorption treatment. The result was considerably less control of train noise in the station without the underplatform treatment, even though the reverberation time in the two stations and the total amount of acoustical absorption per unit volume was about the same for both. The charts on Figure 51 show the large effect of the relatively small area of treatment which can be placed under the platform. In the station where the underplatform treatment was omitted the average noise level was about 5 dBA greater and in the mid- and low-frequencies the difference in noise level was 5 to 8 decibels. This result points out the importance of proper placement of the sound absorbing material. The large noise reductions obtained in the acoustically treated TTC stations and the control of noise in the BART stations depends upon the placement of continuous treatment on the underplatform overhang areas to obtain the full potential for limiting platform noise.

Because of the geometry of the CTA tunnel stations the priorities for location of sound absorption treatment in the platform areas should be as follows:

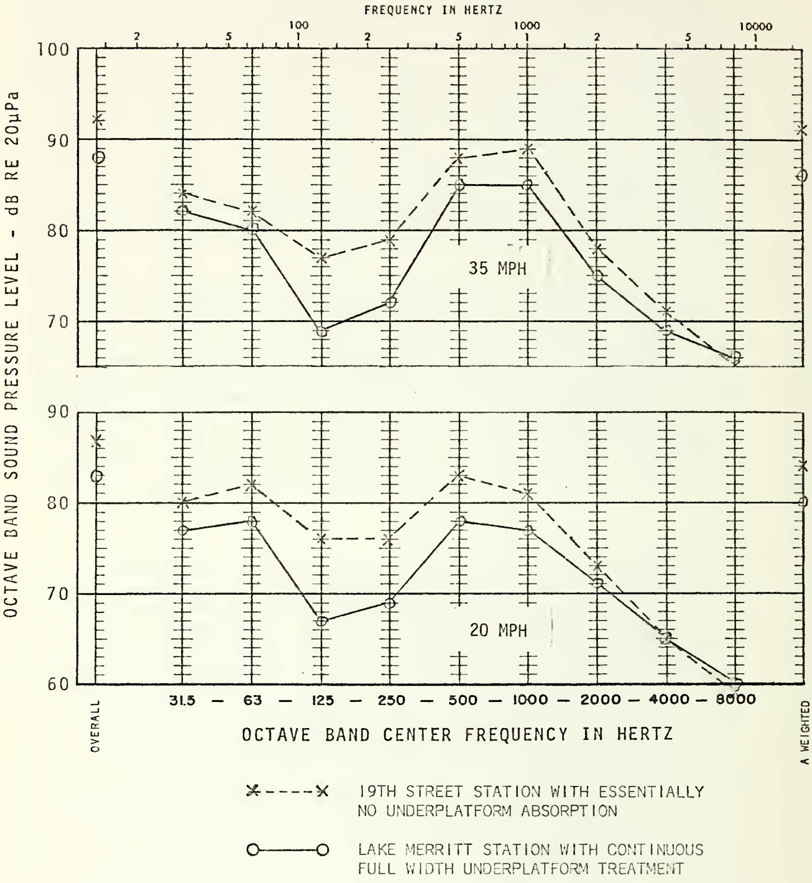


FIGURE 51 NOISE LEVELS ON ACOUSTICALLY TREATED BART SUBWAY STATION PLATFORMS WITH TRAINS PASSING THROUGH AT CONSTANT SPEED

1. Underplatform edge surfaces
2. On side walls opposite platform, from invert to platform level
3. On platform area ceilings in the central arch area
4. On the running tunnel ceiling outboard of the tunnel centerline
5. On the tunnel side walls opposite the platform from platform height to about 9 ft above the platform

As indicated by the listing and discussion above, in reducing noise from the trains the optimum location for the sound absorption treatment is in close proximity to the principle noise sources under the cars, i.e., in close proximity to the noise generated by the wheel/rail interaction and the car propulsion systems. In the listing it is indicated that the highest priority on placement of treatment is for treatment on the underplatform overhang surfaces and the lower side walls opposite the platform. The next priority is the platform ceiling and then the running tunnel ceiling and side walls. The reason the running tunnel ceilings and side walls are not included as a higher priority is because there must be some distribution of the sound absorption material in the room in order to achieve good results and because material located under the platform edge and on the lower side wall opposite the platform is not in the optimum location for reducing reverberation in the main part of the platform space nor is it in the optimum location for reducing noise from other sources such as the crowd noise or station equipment noise. The priority list, therefore, indicates the importance of the acoustical material locations in descending order which will give the best overall results. Thus, if the amount of treatment which can be applied is limited for some reason, either architectural, maintenance or economic, it is most important to place the absorption material on the underplatform overhang surfaces, the lower side walls and the central ceiling area.

A further consideration in determining the optimum location for the sound absorption material is that it is essential for maximum efficiency of the applied material in reducing noise that there be some absorption on both vertical and horizontal surfaces. This is necessary in any enclosed space where acoustical treatment is applied to control noise and reverberation. When the sound absorption is located primarily on either a horizontal surface or on vertical surfaces, the efficiency is reduced because the sound reflections on the surfaces at right angles to the absorbing surfaces are prolonged and have the effect of reducing the overall absorption efficiency. For example, in large rectangular spaces, application of sound absorbing material only on the ceiling can sometimes result in noise and reverberation reduction of only 20% to 30% of the amount expected on the basis of calculations assuming good diffusion or compared to the effectiveness which can be obtained if the same material is distributed uniformly on horizontal and vertical surfaces.

Another very effective procedure for reducing the noise transmitted from the transit trains to the platform area is the inclusion of a platform or ledge on the opposite side of the track from the passenger platform to provide a "channel" which restricts the sound from the wheels and rails and propulsion equipment to the space beneath the car and the platform. All of the noise from transit train operations originates under the car and providing a narrow gap for the noise to escape reduces the noise level transmitted to the station platform areas, particularly when sound absorbing material is included in this restricted underplatform space.

Considering the factors outlined in the above discussion several configurations of possible acoustical treatment for the tunnel stations have been evaluated and the potential results determined. Figures 52 through 57 indicate six configurations recommended for consideration.

All of the arrangements considered include acoustical absorption treatment on or in the arched ceiling area over the center platform in addition to sound absorption material applied to the lower side walls and under the edge of the platform. All of the acoustical treatments discussed herein should be continuous for the entire length of the subway stations. Center platform ceiling treatment would, of course, have to be omitted in those areas where there are escalators, storage rooms or other islands which obstruct the center platform space. The differences in the various recommended configurations are in the sound absorption treatment applications to the running tunnel portion of the station structure.

The treatment areas shown on the drawings are intended to be indicative of those areas which can be and should be considered for the sound absorption treatment application but are not intended to indicate that the arrangements shown are the only recommended configurations. For example, it is not necessary to make the application in all of the areas shown in each instance and, in fact, it may not be possible to place material on some of the surfaces suggested. The drawings are intended only to show those areas which should be given consideration in determining the location and extent of sound absorption treatment to be applied for sound control.

2. Acoustical Treatment Materials

Because the types of acoustical treatments which can be used in a subway station are somewhat limited and subject to stringent requirements, some general information on the characteristics of sound absorption treatments which can be considered for application in the stations are given in the following paragraphs.

For the platform areas it is recommended that a sound absorption treatment with high sound absorption coefficient be used for a number of reasons. This requires the installation of a relatively thick treatment, however, it also minimizes the total area of treatment required. The most flexible and probably the most economical material which can be used for this application is glass fiber material either in a flexible, a semi-rigid, or rigid board form [ordinary ventilation duct liner, for example]. Table XV indicates the sound absorption coefficients as a function of frequency that can be expected for various thicknesses of glass fiber sound absorption treatment. It has been assumed for purposes of the table, giving approximate absorption coefficient values, that the density of the material used will be in the range of 2 to 6 lbs/cu ft, the recommended range of density for subway station and tunnel application.

TABLE XV TYPICAL SOUND ABSORPTION COEFFICIENTS TO BE EXPECTED FROM GLASS FIBER SOUND CONTROL MATERIALS MOUNTED DIRECTLY AGAINST A CONCRETE SURFACE

	Sound Absorption Coefficients				
Frequencies in Hz	125	250	500	1000	2000
1" thick Glass Fiber	.08	.30	.65	.80	.85
2" thick Glass Fiber	.20	.55	.80	.95	.90
3" thick Glass Fiber	.45	.80	.90	.95	.90

Because the subway station structures are all concrete and highly reflective at low frequencies, it is essential that the sound absorption treatment have substantial low frequency absorption, as was observed for the "thick" layer of ballast in the tunnels with ballasted track. A 1" thick or a thinner treatment cannot supply this low frequency absorption and it is, therefore, essential that at least some of the treatment be made up of 2" or 3" thick glass fiber blankets or boards.

In Table XV, the absorption coefficients given are for the basic material mounted on or against the concrete surface and without any covering. For subway station applications it is essential in most instances that the material be enclosed in a sheet plastic or plastic film bag or wrapping for protection, to prevent the accumulation of dust, and to permit washing of the surface. If fire resistance requirements preclude the use of a plastic film, the covering can be made of a tight weave fiberglass cloth. These coverings slightly decrease the high frequency absorption coefficient and slightly increase the middle and low frequency coefficients but essentially have no effect or a slight benefit in terms of reduction of transit train noise.

For the materials mounted on side walls and ceilings in platform areas it is recommended that the minimum sound absorption coefficient be 0.50 at 250 Hz and 0.75 at 500 Hz. This implies then that the treatment should be of 1-1/2" to 2" thickness on the side walls and/or ceilings. Some acoustic materials, such as vinyl or neoprene coated fiberglass or glass cloth faced fiberglass boards, can be painted or are available with appropriate surfaces so that no further facing is required, particularly for a ceiling application. An alternate arrangement is the use of plain glass fiber boards or blankets wrapped in a waterproofing sheet or bag and faced with a perforated sheet metal or other facing. With this latter arrangement the facing material must have at least 30% open area in order to avoid degradation of the sound absorption coefficient.

A possible covering for side wall treatment is perforated sheet metal or plastic with at least 30% open area. Perforation patterns such as: 1/16" diameter holes staggered at 7/64" centers, 1/8" diameter holes at 3/16" centers, and 3/16" diameter holes at 5/16" centers provide adequate open area. There are, of course, other combinations of equivalent performance. Acoustical material applications on ceilings, between structural members on ceilings or in arched ceiling areas could be of pre-formed perforated metal panels with glass fiber behind and with this assembly suspended from or applied directly against the face of the concrete.

A basic panel system could be designed and arranged to provide the acoustical absorption very simply for ceilings and walls. An exposed panel should be of perforated metal, a slit-and-slat configuration of plastic or metal, or some form of architectural trim, which has at least 30% open area and no bars or sections that are greater than 3.0" in width between openings. Such an arrangement will provide for a completely transparent acoustical face. Acoustical material can then be located at 1/2" or larger distance behind the face and could be the simplest and most economical glass fiber blanket or board, i.e., ventilation duct liner material in 1-1/2" or 2" thickness.

One type of sound absorption treatment not discussed above but which could be used at the ceiling center arch is the suspended acoustical tile type of ceiling treatment. A suspended acoustical tile ceiling with an air space between the tile and structural ceiling above can provide adequate low frequency sound absorption to provide equivalent results to a 2" or 3" thick surface mounted treatment. Such an assembly may, therefore, be desirable both economically and architecturally for ceiling treatment in platform areas. This type of treatment is also appropriate for concourse and corridor areas and should be given consideration as a possible treatment for such areas. For platform areas, however, this type of sound absorption assembly requires special consideration because of the static pressure changes which occur during train operations into and through the station patform areas.

The piston action of the trains can cause large air flows and large air pressure differentials to occur, sometimes as great as 10 or 15 lbs/sq ft change in static pressure. Such static pressure changes can result in large forces on suspended acoustical tile ceiling assemblies or, for that matter, any assembly which has an enclosed air space behind the facing material.

If a suspended acoustical tile ceiling system is considered for sound absorption treatment in a platform area, the assembly must include adequate opening for air flow and pressure equalization between the main platform space and the enclosed air space behind the acoustical treatment. In fact, the need for providing gaps for pressure equalization should be considered in all acoustical material applications in subway station platform areas. With proper provision for air flow and pressure equalization, the suspended acoustical tile assembly is a design which can provide adequate and appropriate sound absorption for platform areas.

If suspended acoustical tile ceilings are considered as the acoustical treatment in stations, the minimum thickness of acoustical tile recommended is 3/4" and 1" thickness is preferred. If the assembly selected is a perforated metal pan system then the acoustical material behind the facing should be at least 1" thick glass fiber blankets with appropriate covering to minimize dust and water absorption. Also, because of the static pressure and air flow problem, the acoustical material for metal pan systems should be spaced back from the perforated metal facing by at least 3/8" to 1/2", using a dimpled screen or other support, to provide an air space between the bag enclosing the material and the perforated face.

The sound absorption treatment on the underplatform overhang surfaces should be continuous for the full length of the platforms and should provide as complete coverage of the vertical and horizontal surface as can be accommodated. Openings for ventilation duct registers or locations where there must be access panels or hatches would, of course, be points at which the treatment would be omitted. However, in general, the coverage should be as complete as possible.

The sound absorption treatment can be arranged in a number of manners. Figures 52 to 57 present cross-sectional drawings of several configurations recommended for consideration. There are four basic designs recommended for consideration:

[1] Glass fiber boards or blankets mounted directly against the underplatform overhang surfaces. The glass fiber should be wrapped in a plastic film or glass cloth bag for dirt and water protection and should be provided with an expanded metal or hardware cloth [large mesh screen] cover for mechanical protection and retention.

[2] Wrapped glass fiber blankets or boards with open mesh metal protective facing as in [1] but with the material mounted with an air space between the back of the treatment and the concrete surfaces.

[3] Glass fiber blankets or boards, wrapped in plastic film or glass cloth bags, mounted in and retained by a perforated metal panel [steel or aluminum] and mounted either directly against the concrete surfaces as in [1] or mounted on brackets spacing the panels out from the surfaces as in [2].

[4] Spray-on sound absorption material using a material such as Pyrok, Sound-Shield 85 or Kilnoise as have been used in running tunnels at TTC and WMATA Metro facilities.

For the underplatform acoustical treatment, a material providing a minimum sound absorption coefficient of 0.55 at 250 Hz and 0.75 at 500 Hz is recommended. The best material for this application is 2" or 3" thick glass fiber boards or blankets with a wrapping for water and dust proofing and with some form of metal mesh covering or enclosure for retention and mechanical protection.

A wide range of glass fiber blanket or board materials will give satisfactory performance. The material may be of 2.0

to 6.0 lbs/cu ft nominal density and can be of the rigid, semi-rigid or flexible type. A material with or without sprayed vinyl or neoprene protective coating will be satisfactory and appropriate. Probably the most economical material is glass fiber duct liner as is used in ventilation system ducts. This material is generally least expensive and most readily available in 1" thickness and two or three layers can be used to obtain the 2" or 3" total thickness for the application. Machine room installations of this type have been installed at costs in the range of $1.00 to $2.00 per square foot.

There are a number of procedures available for installing glass fiber boards or blankets directly to concrete surfaces. The most usual procedure for attaching to concrete wall surfaces is a simple mechanical fastening called "Stic Klips". "Stic-Klips are used and attached in the form of large headed nails or a small flat plate and rod assembly fastened to the concrete surface with cement or epoxy such that the shaft or rod sticks straight out from the wall surface. The glass fiber is pushed over the rod and a friction fit washer is placed over the outside surface to retain the material and any protective coverings such as expanded metal, hardware cloth or plastic sheeting. There are other procedures such as the use of metal furring strips or studs fastened to the concrete surface and retaining the glass fiber by a mechanical fastening. Such mountings are convenient when a waterproof covering is to be used.

Dust or dirt collecting on the surface of glass fiber or other absorption material will not significantly affect the sound absorption characteristics, however, if it is desired to protect the material from dirt collection and water absorption, it can be covered or surfaced with polyethylene or mylar film of up to 4 mils thickness without significantly decreasing the noise reduction provided.

If there are fire resistance requirements which preclude the use of plastic film for protective covering and if, in fact, the normal glass fiber board or blanket with resin binder is prohibited because of fire hazard limitations, there are alternate materials of the same type which will provide the same performance. An alternate for the plastic film covering, which gives good protection against water and dust and dirt absorption, is a close weave glass fiber cloth. Because of surface tension a water spray will generally not penetrate the fiberglass cloth, particularly if it is mounted on a vertical surface. To provide a completely fireproof glass fiber material it is necessary to use a material without binder. The Owens-Corning Fiberglas Company provides a material denoted TIW, Thermal Insulating Wool, which has no binder. This is a multi-purpose material for industrial applications at temperatures up to 1000°F and is also denoted M-1000 Insulation for marine applications. Since this material does not have a binder, its use requires an enclosure or bag and a metal framing and screen for retention.

3. Expected Results from Treatment

The various alternates shown on Figures 52 through 57 indicate the recommended configurations for the acoustical treatment with a predicted noise reduction result for each case. Figure 52 is the minimum treatment considered and is a treatment which will provide about 8 to 10 dB reduction. This is less than the reduction provided by ballast and tie trackbed such as used in the Clinton Station structure. The treatment consists of the sound absorption treatment for the central arch, the underplatform treatment on the platform side and a 4 ft wide band of treatment above the existing walkway on the side of the tunnel opposite from the platform.

Better arrangements than Figure 52 are indicated on Figures 53 and 54. The treatments consist of absorption on the ceiling over the center of the platform between the column lines, sound absorption treatment under the platform and bands of sound absorption treatment in the running tunnels. The tunnel wall treatment may all be located on the lower side walls or a combination of lower side wall and tunnel ceiling. This treatment will provide 12 to 14 dBA reduction of the noise, which is comparable to the reduction provided by the ballast and tie trackbed in the Clinton Station structure and will subjectively reduce the sound level to less than half its present value.

The subjective effect of noise reduction in a reverberant space is always a little greater than predicted by comparing of sound levels alone, which can be done out-of-doors in an open space. This is because when the reverberation is reduced the sound tends to come predominantly from one direction, whereas when the reverberation is great the sound tends to impinge on the observer from all directions, giving it an "overwhelming" quality in comparison to the same sound level in a less reverberant or non-reverberant space.

Other configurations are shown on Figures 55 through 57 and the expected results are also given on the sketches. Three suggested configurations include a modification of the walkway to provide a confined space beneath the car and thus minimize the noise transmission to the platform area. This arrangement is a preferred arrangement acoustically, however, it would probably be expensive to provide the modification of the walkway.

One further factor that should be considered in acoustic treatment is the noise transmitted from running tunnels to platforms or from adjacent untreated areas in the long platform stations. To avoid higher noise levels at the ends of a platform than would be experienced at the center, sound absorption treatment should be included for a distance of at least 200 ft beyond each end of a treated platform. In the running tunnels beyond each end of a platform this treatment could consist of a spray-on material or it could be panels similar to the underplatform surface treatment.

4. Summary

For reduction of train noise on subway station platforms, the considerations and recommendations can be summarized as follows:

[1] The most appropriate and economical procedure for reduction of platform noise is the application of sound absorbing material. Reductions of 10 to 15 dBA can be expected.

[2] Sound absorption on the underplatform and the lower part of the side walls is the most important part of the treatment but this must be accompanied by ceiling and possibly wall treatment to give good overall sound control in the platform areas.

[3] Sound absorption treatment on underplatform overhang surfaces should consist of complete coverage of the surfaces with 2" to 3" thick glass fiber boards with a plastic or glass cloth bag for dirt and water protection and an expanded metal, perforated metal or other facing for mechanical protection. Alternately a 1-1/2" thick application of spray-on absorption material could be used.

[4] For side wall and ceiling applications the sound absorption treatment should be of 1-1/2" to 2" thickness glass fiber material with protective and architectural trim facing. For the arch ceilings a suspended acoustical tile ceiling could be used but requires appropriate considerations for air pressure relief.

[5] Sound absorption treatment should be extended at least 200 ft along the tunnels to each side of a treated platform to obtain full benefit from the platform area treatment.

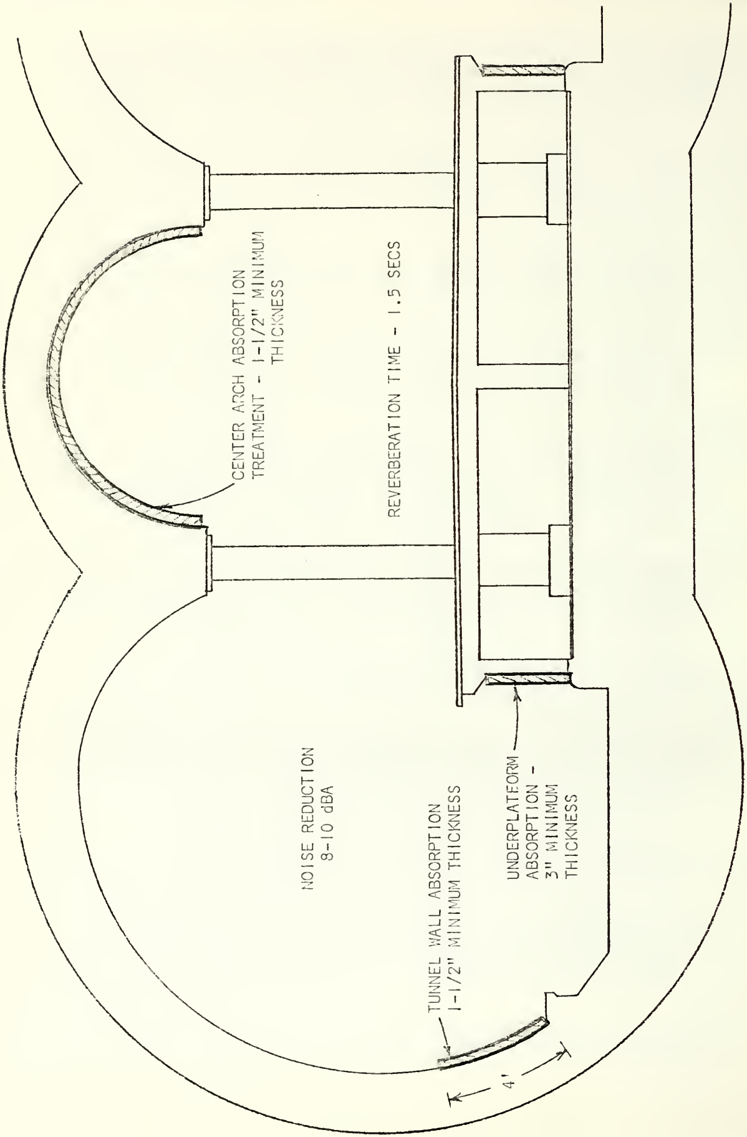

CENTER ARCH ABSORPTION TREATMENT - 1-1/2" MINIMUM THICKNESS
REVERBERATION TIME - 1.5 SECS
NOISE REDUCTION 8-10 dBA
TUNNEL WALL ABSORPTION 1-1/2" MINIMUM THICKNESS
UNDERPLATFORM ABSORPTION - 3" MINIMUM THICKNESS
4'

FIGURE 52 BASIC ABSORPTION TREATMENT CONFIGURATION FOR TUNNEL STATIONS WITH CONCRETE TRACKBED - WILL REDUCE TRAIN NOISE 8-10 dBA

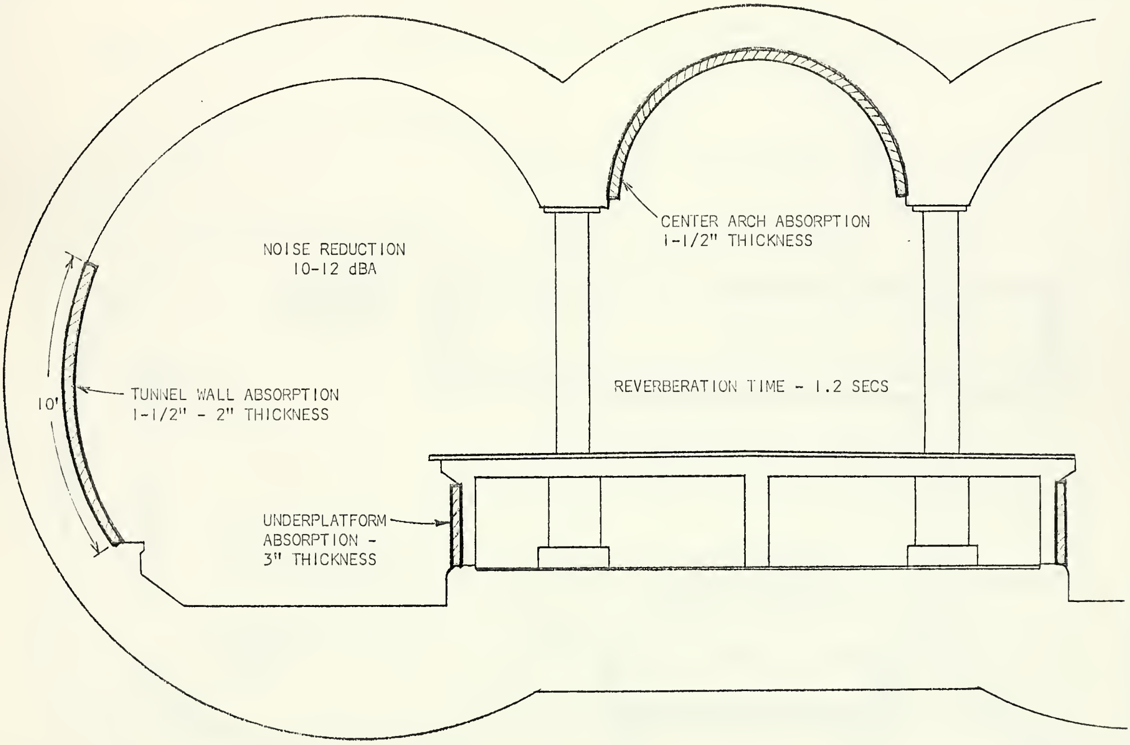


FIGURE 53 MINIMUM RECOMMENDED ABSORPTION TREATMENT FOR NOISE REDUCTION IN TUNNEL STATIONS WITH CONCRETE TRACKBED - WILL REDUCE TRAIN NOISE 10-12 dBA

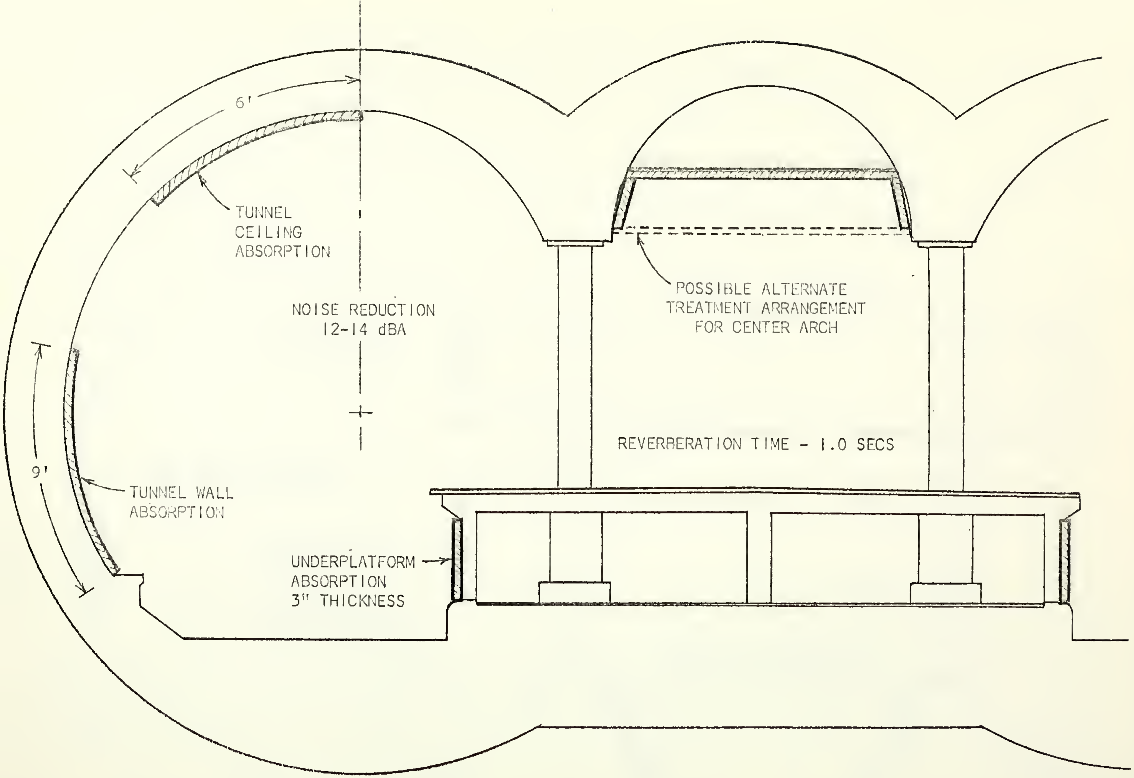

6'
TUNNEL CEILING ABSORPTION
NOISE REDUCTION 12-14 dBA
POSSIBLE ALTERNATE TREATMENT ARRANGEMENT FOR CENTER ARCH
REVERBERATION TIME - 1.0 SECS
9'
TUNNEL WALL ABSORPTION
UNDERPLATFORM ABSORPTION 3" THICKNESS

FIGURE 54 RECOMMENDED ABSORPTION TREATMENT CONFIGURATION - WILL ACHIEVE 12 TO 14 dBA REDUCTION OF TRAIN NOISE IN TUNNEL STATIONS WITH CONCRETE TRACKBED

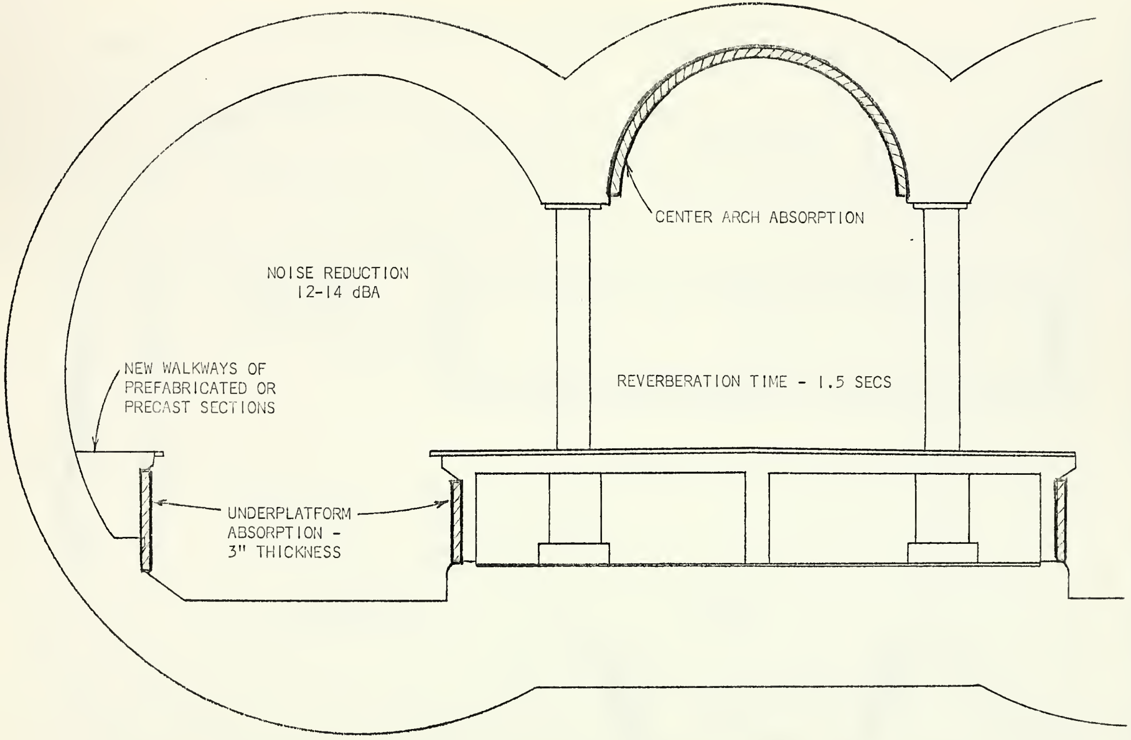

CENTER ARCH ABSORPTION
NOISE REDUCTION 12-14 dBA
REVERBERATION TIME - 1.5 SECS
NEW WALKWAYS OF PREFABRICATED OR PRECAST SECTIONS
UNDERPLATFORM ABSORPTION - 3" THICKNESS

FIGURE 55 MINIMUM SOUND ABSORPTION TREATMENT RECOMMENDED WITH ADDED WALKWAY LEDGE FOR CONFINING NOISE BENEATH THE TRANSIT CARS - 12 TO 14 dBA REDUCTION OF TRAIN NOISE ON PLATFORM

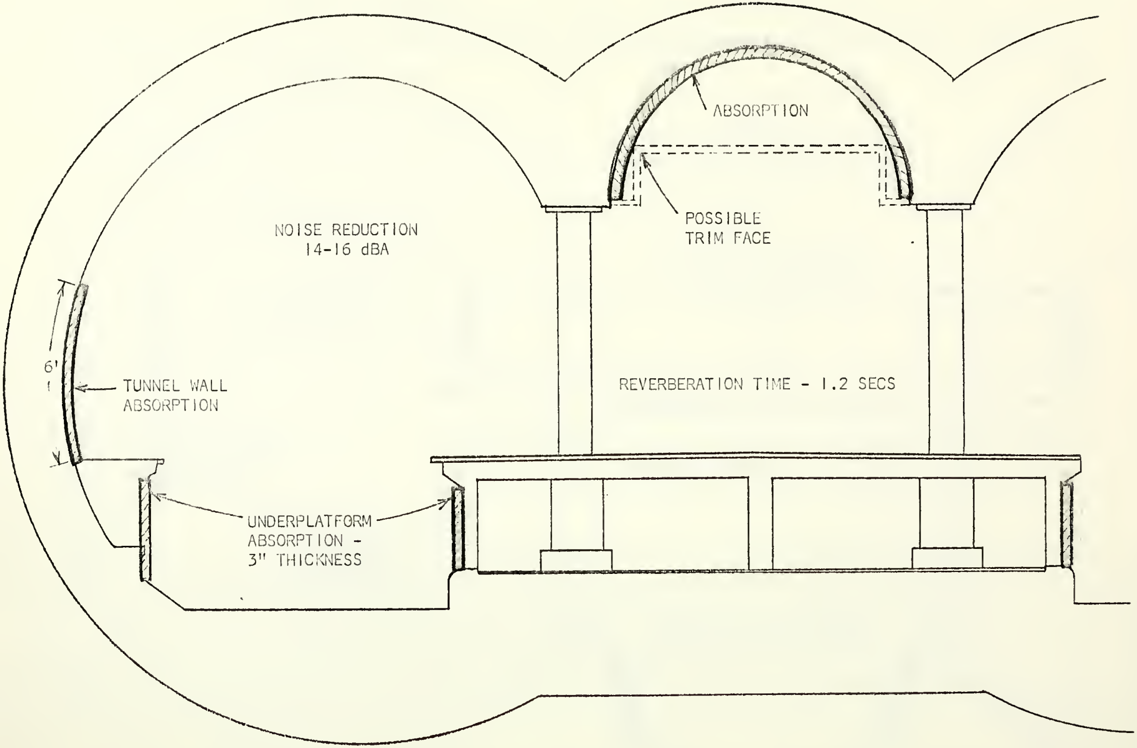

ABSORPTION
POSSIBLE TRIM FACE
NOISE REDUCTION 14-16 dBA
REVERBERATION TIME - 1.2 SECS
6'
TUNNEL WALL ABSORPTION
UNDERPLATFORM ABSORPTION - 3" THICKNESS

FIGURE 56 RECOMMENDED ARRANGEMENT OF STATION TREATMENT WITH MODIFIED WALKWAY - 14 TO 16 dBA REDUCTION OF TRAIN NOISE ON PLATFORM

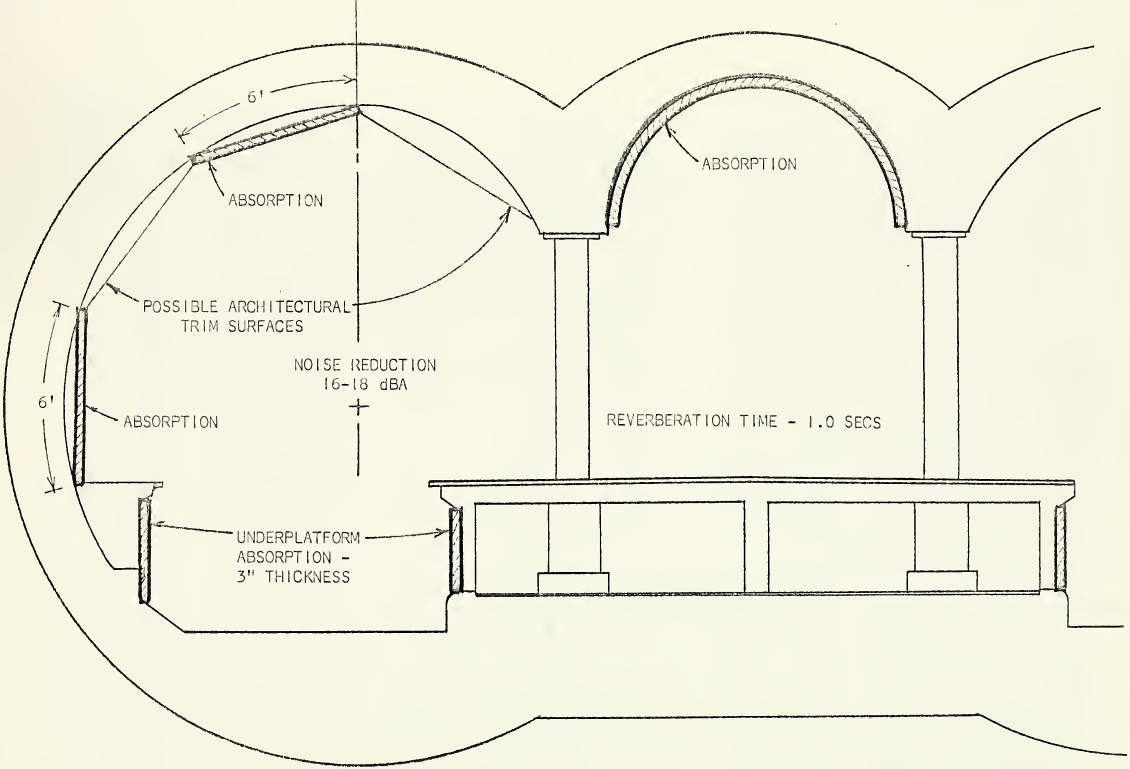

6'
ABSORPTION
ABSORPTION
POSSIBLE ARCHITECTURAL TRIM SURFACES
NOISE REDUCTION 16-18 dBA
6'
ABSORPTION
REVERBERATION TIME - 1.0 SECS
UNDERPLATFORM ABSORPTION - 3" THICKNESS

FIGURE 57 ABSORPTION AND WALKWAY MODIFICATION WHICH WILL GIVE THE MAXIMUM NOISE REDUCTION WHICH CAN BE ACHIEVED BY APPLICATION OF ABSORPTION TO WALL AND CEILING SURFACES

E. Reduction of Elevated Structure Noise

The noise produced by transit train operations on the steel elevated structures is due to the very high level of vibration amplitudes which occur due to the excitation forces from the wheel/rail interaction as the transit trains roll on the elevated structure rail. These very high vibration levels have been documented in one report by Silver and Venema* which presents measurements indicating peak vibration levels of the structure in the range of 20 to 46 g. This study, however, presented no information on the spectra of the vibration which could be related to noise generation.

Another study by the Chicago Department of Environmental Control included measurements of elevated structure vibration with spectral analysis. However, in that case the data analysis was done using an instrument which gave erroneous readings for high vibration levels and most of the information for the higher train speeds, as given in that report, cannot be used because of the analysis error.

Figure A20 in the Appendix indicates one set of elevated structure vibration levels which were made during this study. The vibration levels measured showed good correlation with the wayside noise but, in any case, it is apparent that the noise from elevated structure operations is due to vibration of the elevated structure, considering either the level of wayside noise or car interior noise compared to the levels found for ballast and tie operations and for equipment noise. Reduction of the elevated structure noise, therefore, requires reduction of the structure vibration levels which means reducing the excitation forces applied to the structures.

The only procedures available for reduction of the elevated structure vibration are [1] the changing of the jointed rail to continuous welded rail and [2] providing some form of vibration isolation for the rail to reduce the forces transmitted to the elevated structure. A change from jointed to continuous welded rail should result in a reduction of 8 to 10 dBA judging from the results obtained for the ballast and tie tests, see Figure 15. The alternate procedure of providing vibration isolation between the rail and the structure could provide 6 to 8 dBA reduction of the noise radiated by the elevated structure, without changing the rail, and 10 to 20 dBA reduction with a change of rail, if the isolation can be accomplished in an appropriate manner.

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*"Field Measurements of the Vibration Properties of Elevated Rapid Transit Structures", Thomas Vemema and M. L. Silver, December 1974

Effective vibration isolation of the rail from the elevated structure requires placing a resilient element and mass between the rail and the elevated structure. The mass must be attached to the rail and isolated from the aerial structure on rubber or other resilient mounts. This procedure would provide, in effect, an inertia base mounting for the rail with vibration reduction element between the inertia base and the supporting structure to reduce the transmission or transmissibility of vibration forces and amplitudes.

It has been demonstrated and it is reasonable to expect that the use of resilient direct fixation fasteners such as those used by BART on concrete elevated structure and on concrete invert in subways would not give significant reduction of vibration from the elevated structure. Such resilient direct fixation tie fasteners are excessively stiff for CTA elevated structure applications and do not provide a mass or inertia base between the rail and the resilient element. The vibration forces thus are transmitted relatively unattenuated to the light weight steel elevated structure and such an installation would not be effective in reducing noise radiated by the elevated structure.

The ideal arrangement for vibration isolation of the rail from the elevated structure would be to provide a concrete slab for support of the rail, in the place of the existing wooden ties, with rubber pads for support of the concrete slab on the elevated structure. This would be an arrangement similar to the floating slab trackbed design for subways at the WMATA Metro, the TTC and the MARTA systems. Unfortunately, because of the load support limitations on the elevated structure this is probably not a practical design that could be considered. The minimum weight of such a slab would be on the order of 800 to 1000 lbs/linear ft of structure per track, a weight approximately equivalent to the transit car weights. This is probably in excess of the capability for increased weight load on the elevated structure.

An alternate procedure to a concrete deck and a design which is suggested for consideration is an adaptation of the RS-STEDEF resilient tie system for application to the elevated structure. The design recommended for consideration is the use of the RS-STEDEF 2-block concrete tie in the configuration used for vibration isolation in subway applications. This design consists of the standard tie molded to be used with a rubber boot and expanded closed-cell neoprene pad placed in a recess in the concrete invert. For the elevated structure application the ties could be fixed to the structure with fabricated steel cups or retainers welded or bolted to the structure as suggested by the sketch on Figure 58. This arrangement would provide for some mass between the rail and the vibration isolation element. The fixation for the ties and rails would be provided in the standard manner as for subway applications of the RS-STEDEF resilient tie assembly, but the ties, rubber boots and pads would be placed in steel pockets on top of the elevated structure instead of being set in pockets in a concrete invert. This assembly could be arranged to replace the existing wooden ties and probably could be accomplished without significant change in elevation of the running rails. It is difficult to predict the noise reduction to be expected from such an arrangement, however, it is expected that 5 to 15 dB reduction would be achieved.

The RS-STEDEF ties weigh approximately 400 lbs each so that in terms of weight added to the structure the maximum addition for this design suggestion would be about 200 lb/ft of structure per track, assuming 24" O.C. spacing for the ties. There would be some reduction in dead weight load due to the removal of the wood ties although this would probably be offset by the steel retainer cups required for the rubber boots and ties. It should be remembered in analyzing this design that the dynamic forces applied to the structure would be reduced and this could be sufficient to permit an increased dead load weight on the structure.

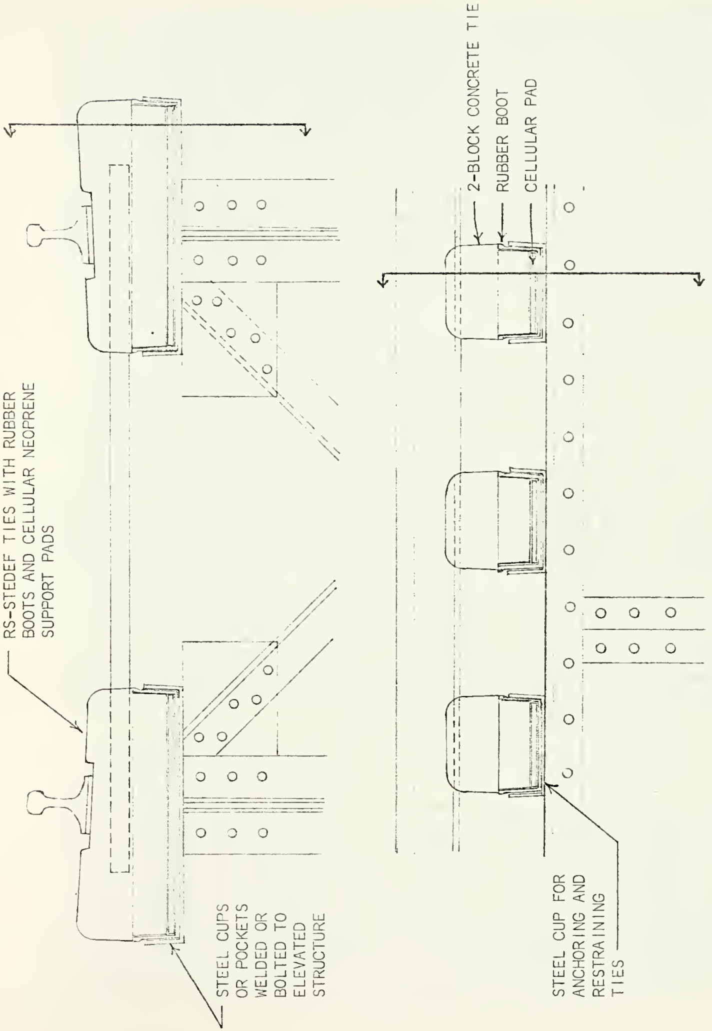

RS-STEDEF TIES WITH RUBBER BOOTS AND CELLULAR NEOPRENE SUPPORT PADS
STEEL CUPS OR POCKETS WELDED OR BOLTED TO ELEVATED STRUCTURE
2-BLOCK CONCRETE TIE
RUBBER BOOT
CELLULAR PAD
STEEL CUP FOR ANCHORING AND RESTRAINING TIES

FIGURE 58 SUGGESTED CONFIGURATION FOR VIBRATION ISOLATION OF ELEVATED STRUCTURE RAIL USING THE RS-STEDEF RESILIENTLY SUPPORTED TIE CONCEPT

VI. FURTHER MEASUREMENTS AND EVALUATIONS RECOMMENDED

The measurement series conducted and reported as a part of this study present a fairly complete review of the noise characteristics of the CTA system rail transit vehicles and way structures. The findings do indicate some areas where further study should be done to clarify some points and there are some experiments or test installations which should be tried to determine the benefits to be obtained.

One of the questions raised by the data for the wayside and in-car sound levels in the subways with ballast and tie track compared to the tunnels with concrete trackbed, is the degree to which the noise reduction with ballast may be due to different levels of rail vibration. It may be that the ballast and tie track fixation results in some damping of the rail which would result in lower rail vibration levels and, therefore, lower noise radiation from the rail. It could also be that the roughness of the rail was less for the ballast and tie track installations, a situation that would also result in lower vibration level of the rail and lower noise radiation. To confirm that the noise reduction was indeed all or at least mostly due to the absorptive effect of the ballasted trackbed, it is suggested that a series of measurements be done which would include measurement of the rail vibration level simultaneous with measurements of the noise. Such measurements could be accomplished by instrumenting the rail with accelerometers at a location in ballasted subway and at a location in concrete trackbed subway. Measurements should then be made of the noise levels in the cars and in the subway at the same time as recordings of the rail vibration level are made. Comparison of the rail vibration level readings would give an indication of the noise source levels and thereby provide a means for correcting or normalizing the noise measurements in a manner to correspond with any differences in noise source levels. This would then provide means for determining the exact degree of noise reduction which is due to the ballasted trackbed.

If rail vibration measurements in the two types of subway could be made at a time when both sets of rails had been recently smoothed and were in essentially the same condition with regard to roughness, the data could be used to indicate any damping effect of the ballast and tie track relative to the rigid fixation system used in the concrete trackbed tunnels. Such data would lead to determination of potential benefit to be obtained from rail damping in reducing of noise in untreated subways. All evaluations to date with regard to rail damping have indicated negligible benefit, however, the excellent noise reduction results observed for the CTA ballasted track subways do raise the question of possible benefit due to damping reducing the rail vibration levels.

Another factor which should be investigated more thoroughly is the effectiveness of soft journal sleeves at the axles in reduction of noise generated by the wheel/rail interaction which results in both reduced wayside noise and reduced car interior noise. Cars 2173/74 which were equipped with the very soft journal sleeves exhibited substantially reduced levels relative to unmodified cars. The reduction of the journal sleeve stiffness on the experimental basis was a 30 to 1 reduction, from stiffness of 500,000 lb/in to a stiffness of 17,500 lb/in. With such soft journal sleeves the deflection of the axles in the housings was so large that the cars could not be operated with passenger load because of contact between the axle and housing. It is probable that most of the reduction in noise generation and, therefore, most of the reduced noise levels observed for this modification of the 2000 series cars could be accomplished with a much less severe reduction of stiffness.

It is suggested that consideration be given to accomplishing a series of tests with a car equipped with journal sleeves of stiffness on the order of 50,000 lb/in, i.e., 1/10 the stiffness of the standard journal sleeves. This would reduce the deflection under load to only 1/3 the value with the very soft sleeves, but should be sufficiently soft to give most of the noise reduction and ride quality improvement that was observed with the test installation. If a softer journal sleeve installation, which is satisfactory for in-service use, does indeed give noise reduction similar to, or even approaching that observed with the experimental test train, this would certainly indicate a relatively inexpensive way to obtain substantial reduction of noise for operations of the 2000 series cars. For the train with soft journal sleeves the interior noise was up to 8 dBA lower than for the standard unmodified 2000 series cars. Similarly, there was 5 to 6 dBA reduction of car interior noise and 3 to 5 dBA reduction of wayside noise compared to the 2000 series cars with overhauled and modified trucks. These reductions are substantial and if the results could be confirmed with use of a configuration of soft journal sleeve that is acceptable for service use, this would indeed be an inexpensive means of achieving substantial noise reduction.

As has been indicated on many occasions, a series of tests with resilient wheels would be very useful in determining the potential for overall system noise reduction. There is evidence that resilient wheels of the Penn Machine Company - Bochum type - do significantly reduce roar noise for operation in subways and it is well known that they reduce or virtually eliminate wheel squeal noise. Similar results are obtained for other resilient wheels such as the Acoustaflex and SAB wheels. It is recommended that continuing efforts be made to obtain a 2-car or 4-car set of resilient wheels which could be used for tests to demonstrate the noise reduction potential of such a modification to the transit cars.

It should be mentioned that the type of resilient wheel recommended is one which is considerably stiffer than the PCC streetcar wheels, with much less static deflection. Such a resilient wheel should not contribute to rail corrugation and, in fact, should result in reduced rail wear and reduced formation of corrugation. Tests at the TTC facilities have indicated that the Bochum type resilient wheel has considerably greater wear life than a standard solid steel wheel, probably due to the effects of the resilience in reducing dynamic forces at the wheel/rail interface. If indeed the resilient wheels prove to have longer life than standard wheels, this should certainly compensate for the increased cost for the resilient wheels. Thus, the noise reduction benefits may be available for little or no increase in the life cost of the transit car wheels.

While it is recognized that there are few possibilities available and questionable chance for success in reducing noise from the existing steel elevated structure, it is recommended that consideration be given to installation of a test section of resilient mountings for the rail using a configuration similar to that recommended in this report. A test installation of only 200 to 300 ft length would be sufficient to determine the effectiveness and dynamic characteristics of such a design. A test installation would also determine the feasibility and practicality of making a change in the rail mounting system on the elevated structure.

Demonstration of the effects of acoustic treatment in subway stations and acoustic treatment in subway running tunnels with concrete trackbed could be made with trial installations covering relatively short sections of running tunnel or subway station platforms. On an experimental basis it is suggested that an installation could be made using prefabricated perforated sheet metal or expanded metal panels with fiberglass, to be mechanically fastened with powder actuated studs. Such panels can be constructed for a cost in the range of $2.00 to $4.00 per sq ft. The installations could be made in staged or step-by-step fashion in station platform areas or running tunnels, or both, in order to provide an installation of sufficient length to demonstrate the benefit. In this case it is recommended that the test installation length be on the order of 400 to 600 ft in order to have sufficient length of treated subway to show the full benefit of the absorption treatment. For an application at a subway station platform the adjacent tunnel beyond the end of the platform should be treated for a length of at least 100 ft to reduce the noise from trains operating in the tunnel which is transmitted to the platform via the tunnel.

Because there is no definitive information on the effects of rail smoothing or grinding and the reduction of noise from operations on the jointed rail, it is suggested that a test of the effect of rail smoothing on jointed rail be considered. This should be tried both on the ballast and tie jointed rail and on the elevated structure jointed rail. To give the maximum effectiveness the type of rail grinder which should be used on the jointed rail should be a rotating abrasive wheel grinder with long wheelbase rather than the dragging abrasive brick type of rail grinder which has a short wheelbase. The reason for this suggestion is that the long wheelbase abrasive wheel type grinder can remove enough material from the head of the rail to, in effect, align the rail joints along the head of the rail to eliminate step up or step down misalignment at the joints. This should result in minimum noise generation. The abrasive brick type of rail grinder, while very effective in removing corrugation and roughness on continuous welded rail, is not as effective on jointed rail simply because of the nature of the grinding procedure.

VII. SUMMARY

The main purposes of this noise study and the associated measurements of the CTA transit vehicle noise were the determination of the noise levels and noise generation characteristics, the determination of relative magnitudes of noise levels produced by operation on the various types of way structure and by the different types and configurations of vehicles and the determination of the potential for reduction of the noise. The study has included determination of procedures for accomplishing the noise reduction.

The results of the study show that there is potential for significant reduction of the noise levels for those areas and types of operation which are the noisiest. Certainly the study has produced results that show that the equipment and facilities can take advantage of noise reduction modifications to give substantially reduced noise exposure for patrons and, at least in some cases, for wayside neighbors.

The measurements and evaluations presented herein concentrate primarily on the roar noise produced to the wayside and in the cars during normal operations. The evaluation has not included definitive study of wheel squeal noise or impact noise at switches and frogs. Some data was obtained for wheel squeal noise on elevated structure short radius curves, however, the data was not repeatable or very conclusive. Some data was obtained for noise levels in the cars when operating through crossovers, however, since operation through the crossovers is of short time duration compared to other noise exposures for patrons, these results and findings are not discussed but the data is presented in the Appendices.

The most intense noise levels observed for all of the types of operations were found to be the noise levels on subway platforms in the round tunnel stations with concrete trackbed. Following this in intensity and exposure to patrons are the noise levels in the cars operating in the smooth bore tunnels with concrete trackbed. The noise levels in cars on elevated structure are next in order of loudness followed by operations in subways with ballast and tie trackbed. The quietest operation with regard to car interior noise is for ballast and tie track at grade with continuous welded rail. Operation in subways with ballast and tie track was found to be comparable to operation on surface ballast and tie track with jointed rail or worn continuous rail but somewhat noisier than the surface ballast and tie operation on smooth continuous welded rail.

For wayside noise from surface and elevated structure operations, it was found that the wayside noise from surface operations with jointed rail and for operations on the elevated structure are high and that there is little potential for reduction of these noise levels short of changing the rail to continuous welded rail. With continuous welded rail the surface ballast and tie tracks result in wayside noise levels from the trains which are very comparable to new transit systems and, in fact, for some car configurations are quieter than new systems such as BART. Thus, the wayside noise from the ballast and tie track operations with continuous welded rail do not represent a serious or significant community noise problem since the levels are comparable to or less than the noise levels produced by heavy vehicles on the streets and highways.

One of the noise reduction procedures tested during the measurement series was the smoothing of the continuous welded rail. As expected this test showed substantial reduction of the wayside and in-car noise. The tests were done for operations on surface ballast and tie tracks and the smoothing produced noise level reductions of 4 to 6 dBA for wayside noise and similar reductions of interior noise. While not included in the measurements, rail smoothing in subways can produce noise reductions of as much as 6 to 9 dBA.

In overall terms the smoothing of continuous welded rail with a rail smoother is one of the most effective procedures for reducing noise from the train operations. The CTA system does experience roughening and corrugation of the rail in service, which increases operation noise, and periodic smoothing of the rail is essential to obtain the full potential of the other design features which result in low noise or reduced noise level operation. Information on the effects of smoothing on jointed rail is inconclusive although some of the tests on elevated structure, which showed higher sound levels for similar structures in some areas, imply that smoothing of the jointed rail could give some reduction of elevated structure noise.

The only procedure available for reduction of wayside noise from the elevated structures is the reduction of vibration level of the structure which in turn will require some substantial modifications which may or may not be practical, i.e., changing the rail to continuous welded rail, providing vibration isolation for the rail, or both. A possible type of change to the structure, in addition to considering the change to continuous welded rail, is presented in this report.

The sound levels on the subway station platforms for those stations with concrete trackbed where the highest noise levels are experienced by CTA patrons are typically in the range of 105 to 110 dBA. The same transit vehicles operating in stations with ballast and tie track, either tunnel stations or box section stations, produce noise levels on the order of 15 dBA less, i.e., in the range of 90 to 95 dBA maximum. The latter is a considerably reduced noise level demonstrating the potential for reduction of subway platform noise levels which can be achieved by sound absorption treatment applications. Similarly, the car interior noise levels for operation in tunnels with concrete trackbed are in the range of 95 to 100 dBA while the operations for the same vehicles in subways with ballast and tie track are in the range of 85 to 90 dBA, or about 10 dBA less.

The results from both the in-car measurements and subway platform measurements indicate that the reduction is predominantly due to the absorptive effect of the ballasted trackbed. Thus, substantial reduction of the noise on the platforms and in the tunnels can be obtained by applications of sound absorbing materials. In the running tunnels with concrete trackbed the application of sound absorbing material panels or spray-on sound absorbing material to the lower side walls can give reductions of at least 6 to 8 dBA for the car interior noise. With sound absorption treatments which can be applied to the underplatform surfaces, the side walls of the running tunnels, and ceilings of the station platform areas, it is possible to reduce the platform noise levels in the subway stations to much more acceptable levels, at least 12 to 15 dBA less than now experienced, making the platform noise levels much nearer the levels experienced at newer facilities which had acoustical absopriton material installed at the time of construction. Designs and procedures for accomplishing this noise reduction are included in the discussion in this report.

The measurements of the car equipment noise showed that the equipment noise is much lower than the total noise experienced either to the wayside or in the cars for most operating conditions. Only for operation on smooth continuous welded rail on ballast and tie tracks does the noise from the propulsion equipment become significant in the total noise. Comparing the performances of the different cars on structures with jointed rails shows little difference in performance either on the elevated structure or on ballast and tie track. Further, for the elevated structures little difference was found in the wayside noise generated by solid web or open web structures for areas where the rail condition was similar. Some difference was found in car interior noise for different sections of elevated structures, however, this was probably due to differences in rail condition rather than differences in the structure vibration and noise radiation characteristics.

The main differences in the car performances were observed for the 2000 series cars. Tests with three configurations of 2000 series cars were included, a standard train, a train with overhauled and modified trucks, and a train with overhauled trucks having special soft journal sleeves. The results for the tests on these cars showed substantially lowered noise levels for the overhauled and modified trucks relative to the unmodified standard car and even further reduction for the cars with the soft journal sleeves. These reductions were found for all types of operations except for the jointed rail ballast and tie and the elevated structure; the two operating conditions were impact noise from wheel and rail interaction predominates the total noise.

The results from the 2000 series car tests are among the most significant results from this study. The results with the 2000 series cars equipped with soft journal sleeves showed substantial reductions of the wayside and in-car noise relative to all other car configurations, in some cases 6 to 8 dBA less noise than for the standard car configurations. It, thus, appears that modification of the cars in terms of better vibration isolation [softer springs] between the axles and the truck frames does result in reduced wheel/rail noise and reduced transmission of the noise into the transit cars. While the tested configuration was not practical for service it is recommended that a similar type modification, which could be installed on the cars during regular maintenance procedures, be considered. With the softer journal sleeves it is apparently possible to take full advantage of the quiet operating propulsion systems and the absorption in existing ballast and tie track subways to obtain, relatively, very quiet operation of the transit cars.

APPENDIX A

WAYSIDE NOISE LEVELS FOR ELEVATED STRUCTURE OPERATIONS

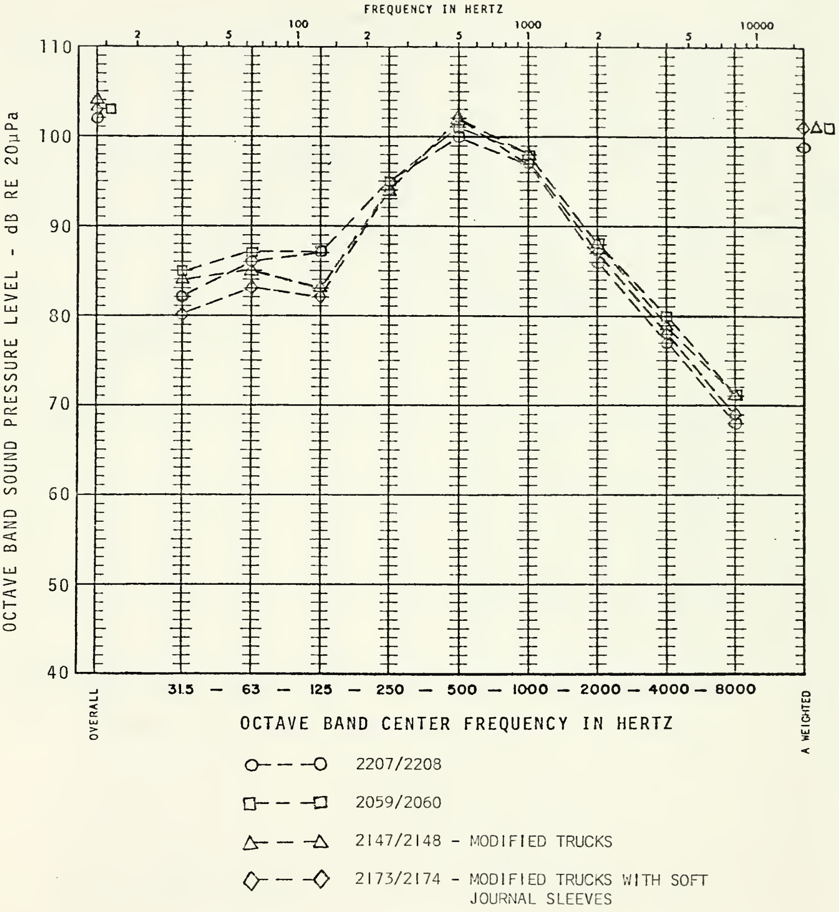


FIGURE A1 WAYSIDE NOISE LEVEL FOR 2-CAR TRAINS ON 2-TRACK OPEN WEB ELEVATED STRUCTURE

50 FT FROM TRACK ℄ - 47 MPH

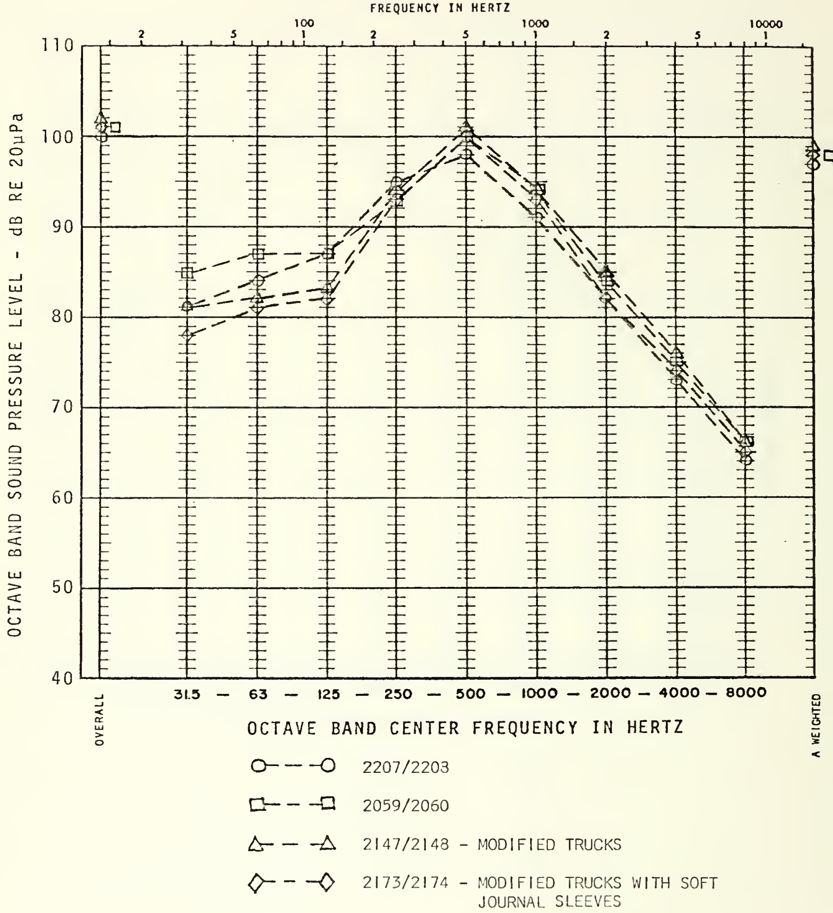


FIGURE A2 WAYSIDE NOISE LEVEL FOR 2-CAR TRAINS ON 2-TRACK OPEN WEB ELEVATED STRUCTURE

50 FT FROM TRACK ℄ - 40 MPH

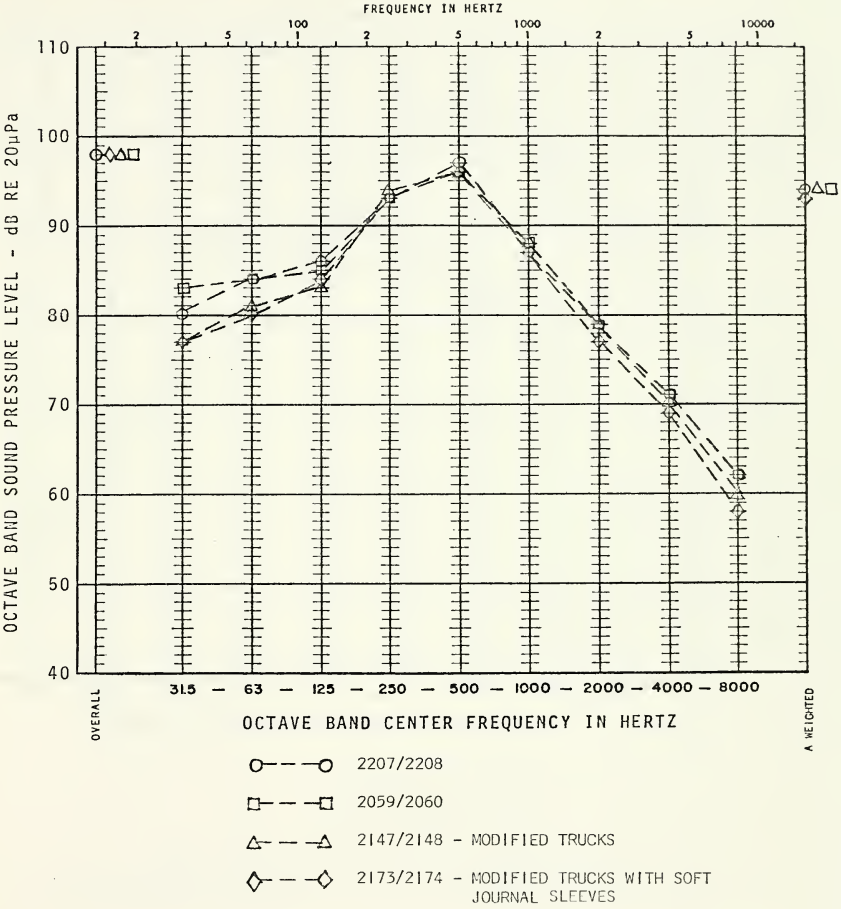


FIGURE A3 WAYSIDE NOISE LEVEL FOR 2-CAR TRAINS ON 2-TRACK OPEN WEB ELEVATED STRUCTURE

50 FT FROM TRACK ℄ - 30 MPH

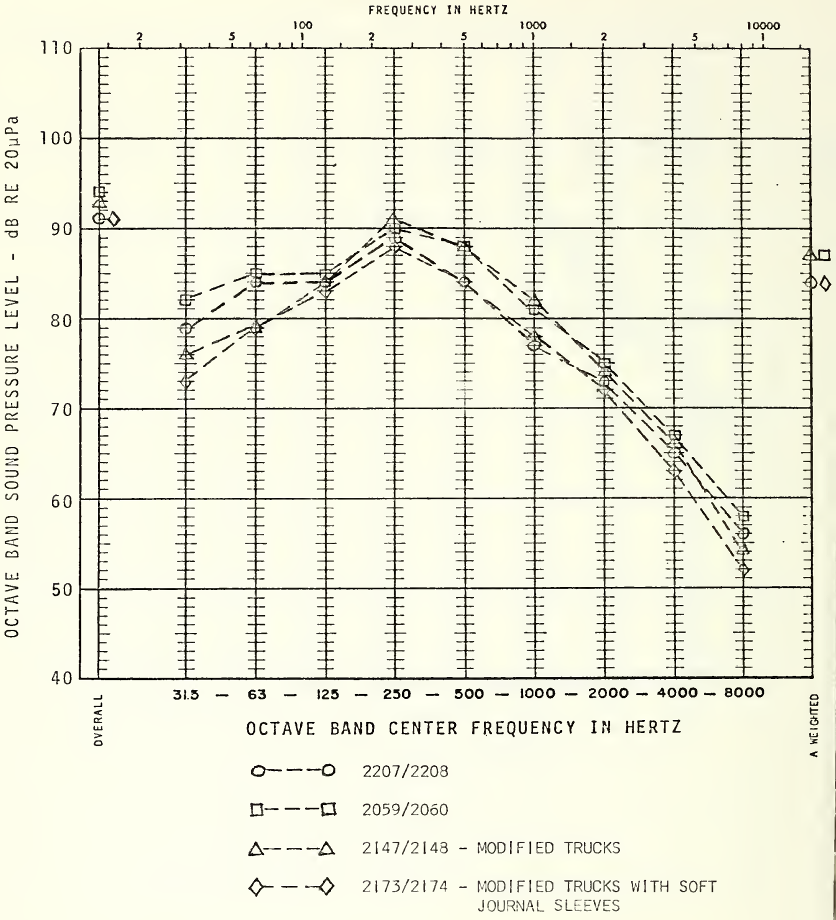


FIGURE A4 WAYSIDE NOISE LEVEL FOR 2-CAR TRAINS ON 2-TRACK OPEN WEB ELEVATED STRUCTURE

50 FT FROM TRACK ℄ - 20 MPH

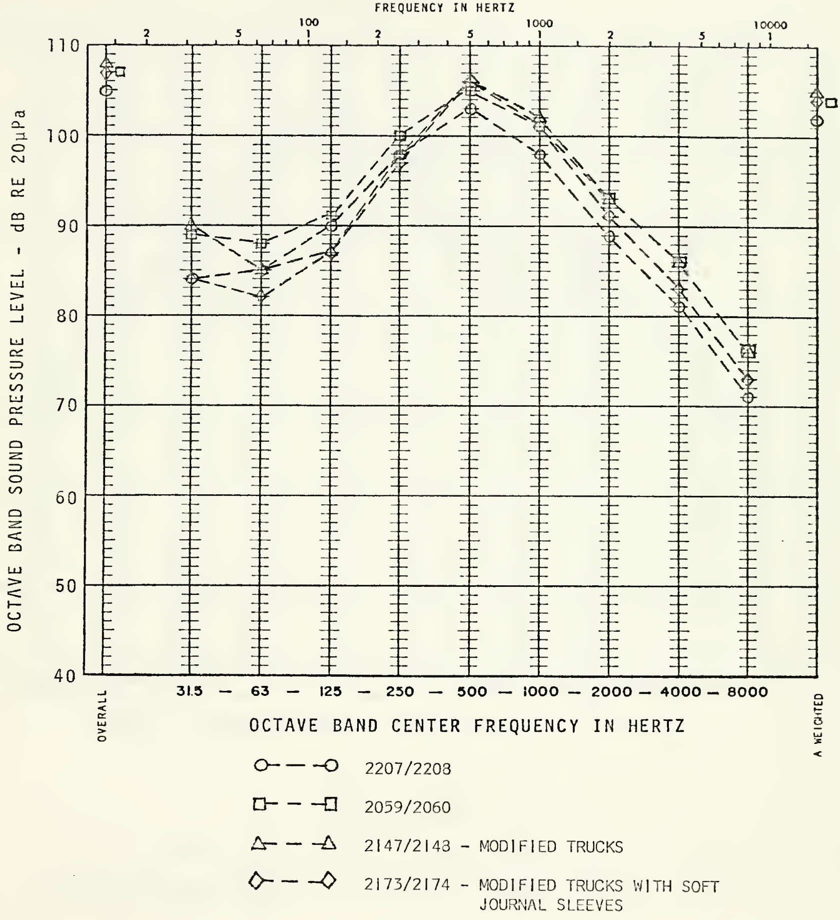


FIGURE A5 WAYSIDE NOISE LEVEL FOR 2-CAR TRAINS ON 2-TRACK OPEN WEB ELEVATED STRUCTURE

25 FT FROM TRACK ℄ - 47 MPH

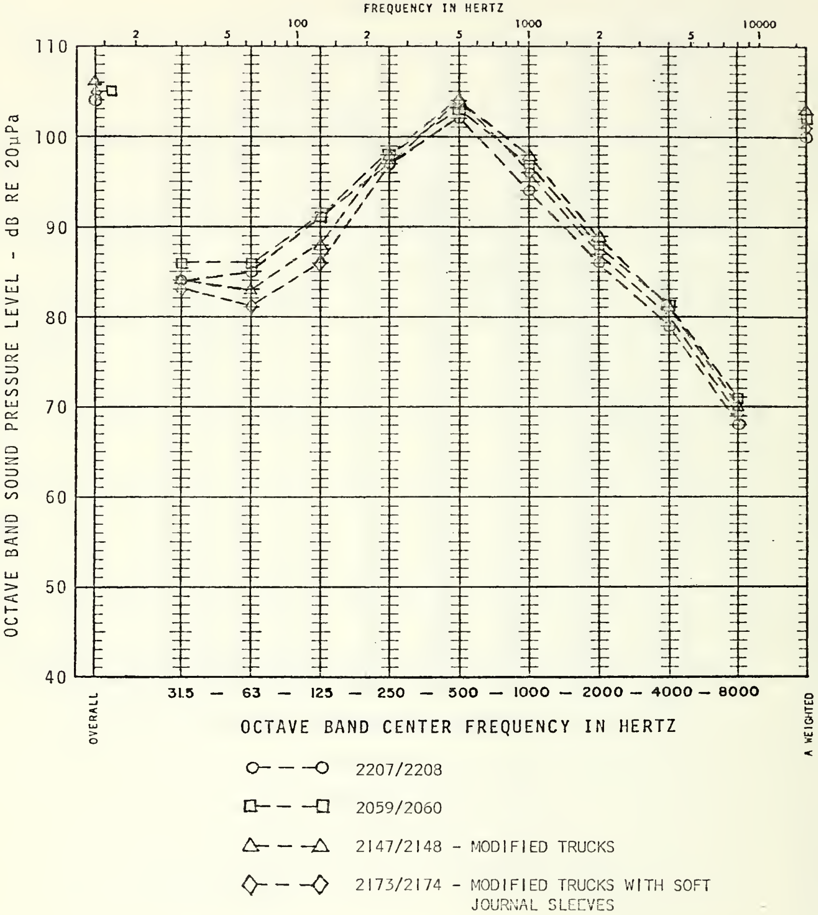


FIGURE A6 WAYSIDE NOISE LEVEL FOR 2-CAR TRAINS ON 2-TRACK OPEN WEB ELEVATED STRUCTURE

25 FT FROM TRACK ℄ - 40 MPH

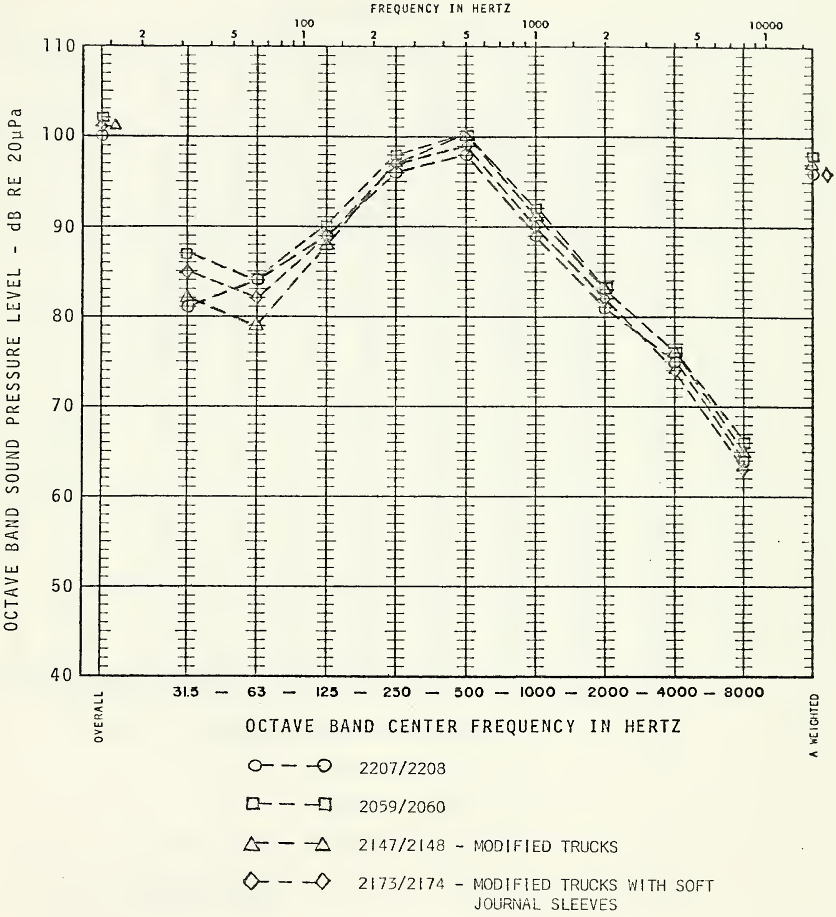


FIGURE A7 WAYSIDE NOISE LEVEL FOR 2-CAR TRAINS ON 2-TRACK OPEN WEB ELEVATED STRUCTURE

25 FT FROM TRACK ℄ - 30 MPH

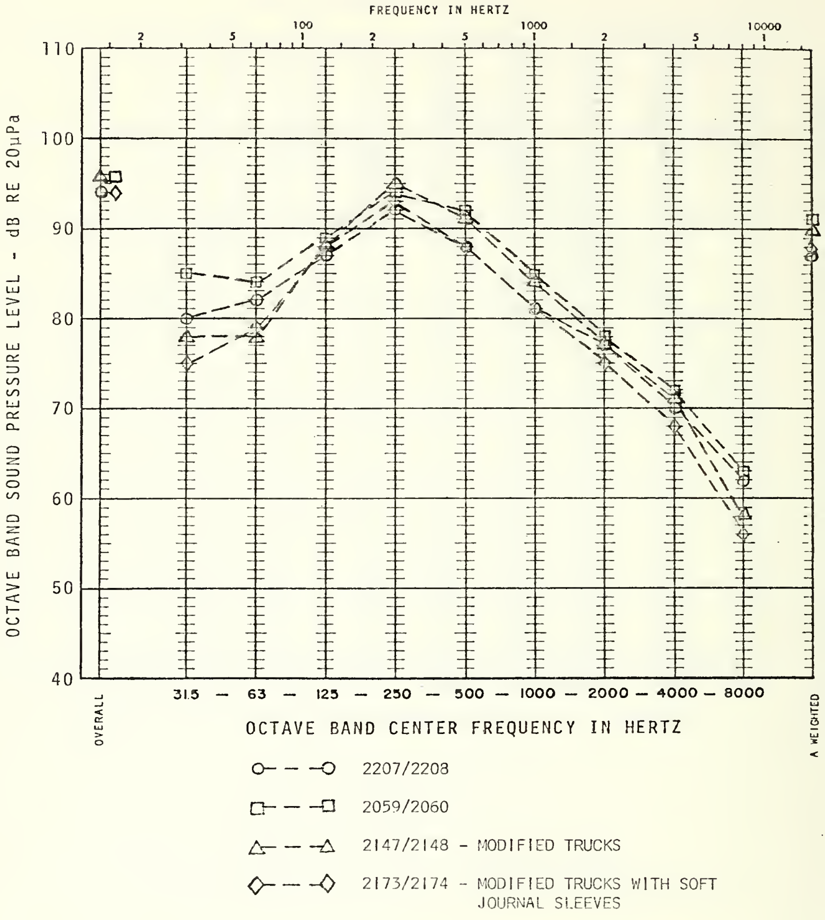


FIGURE A8 WAYSIDE NOISE LEVEL FOR 2-CAR TRAINS ON 2-TRACK OPEN WEB ELEVATED STRUCTURE

25 FT FROM TRACK ℄ - 20 MPH

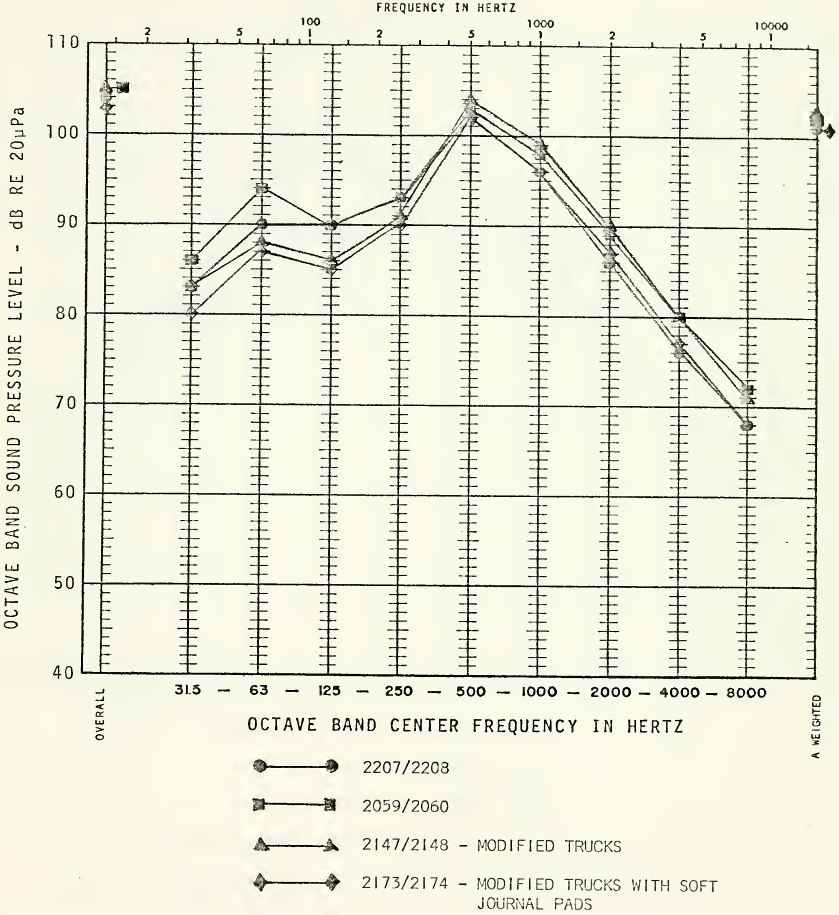
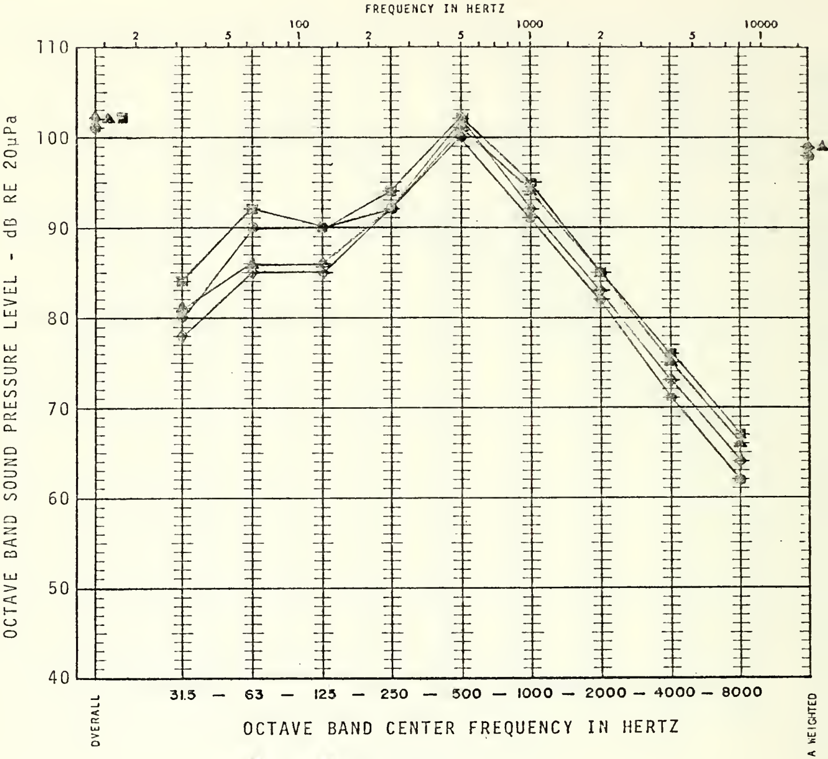


FIGURE A9 WAYSIDE NOISE LEVEL FOR 2-CAR TRAINS ON 4-TRACK SOLID WEB ELEVATED STRUCTURE

50 FT FROM TRACK ℄ - 47 MPH



● 2207/2208

▨ 2059/2060

▲ 2147/2148 - MODIFIED TRUCKS

◆ 2173/2174 - MODIFIED TRUCKS WITH SOFT JOURNAL PADS

FIGURE A10 WAYSIDE NOISE LEVEL FOR 2-CAR TRAINS ON 4-TRACK SOLID WEB ELEVATED STRUCTURE

50 FT FROM TRACK ℄ - 40 MPH

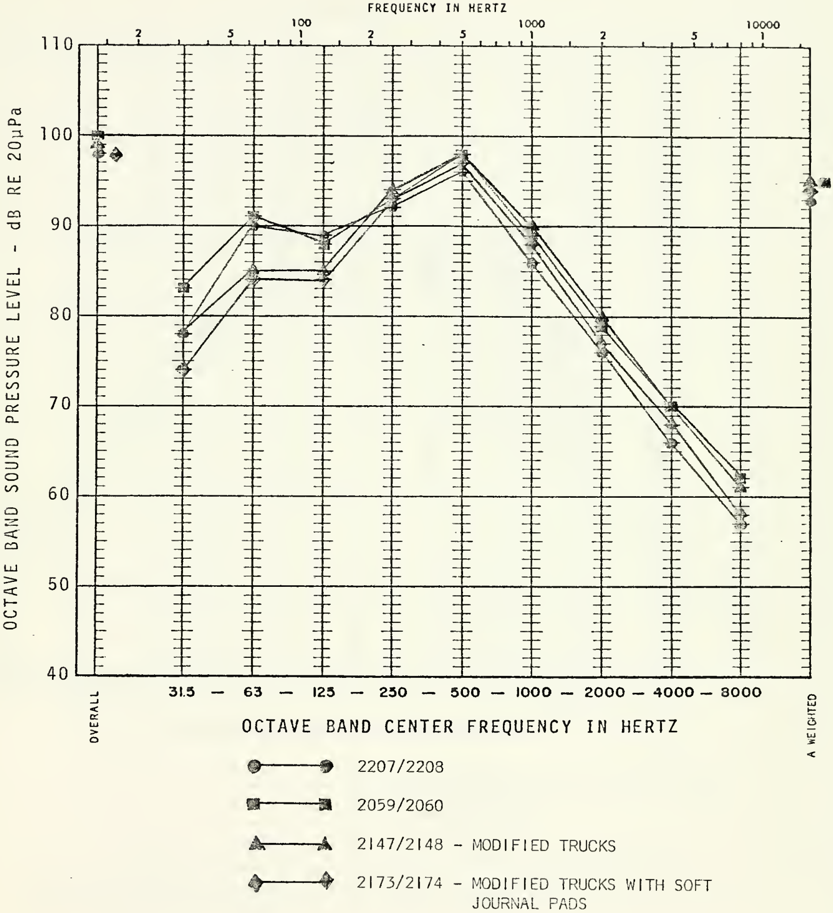


FIGURE A11 WAYSIDE NOISE LEVEL FOR 2-CAR TRAINS ON 4-TRACK SOLID WEB ELEVATED STRUCTURE

50 FT FROM TRACK ℄ - 30 MPH

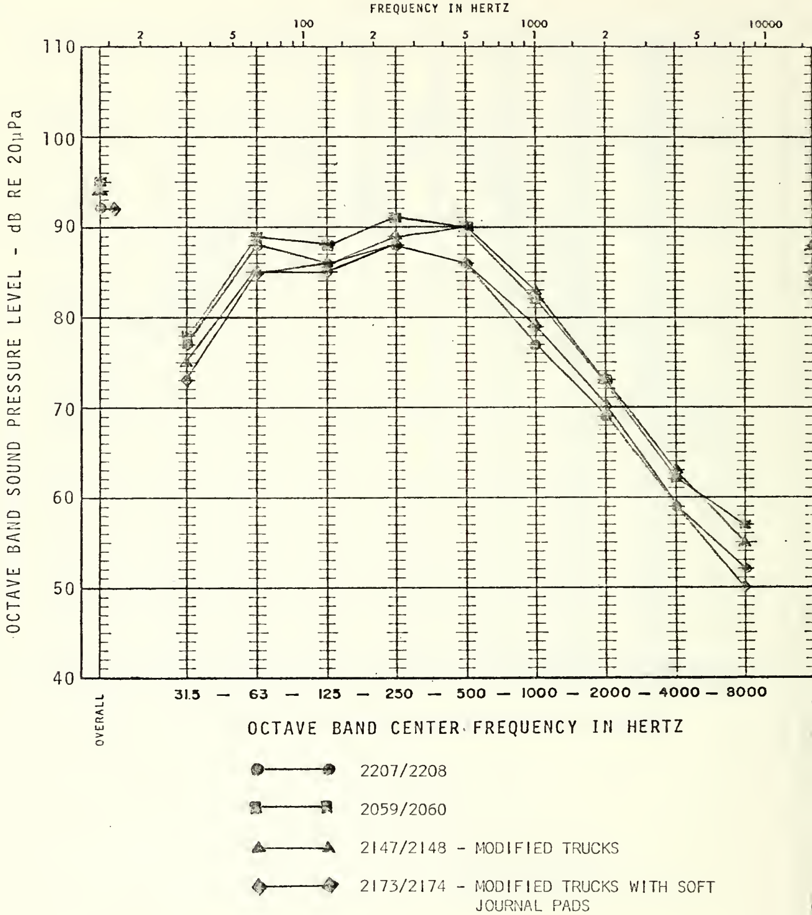


FIGURE A12 WAYSIDE NOISE LEVEL FOR 2-CAR TRAINS ON 4-TRACK SOLID WEB ELEVATED STRUCTURE

50 FT FROM TRACK ℄ - 20 MPH

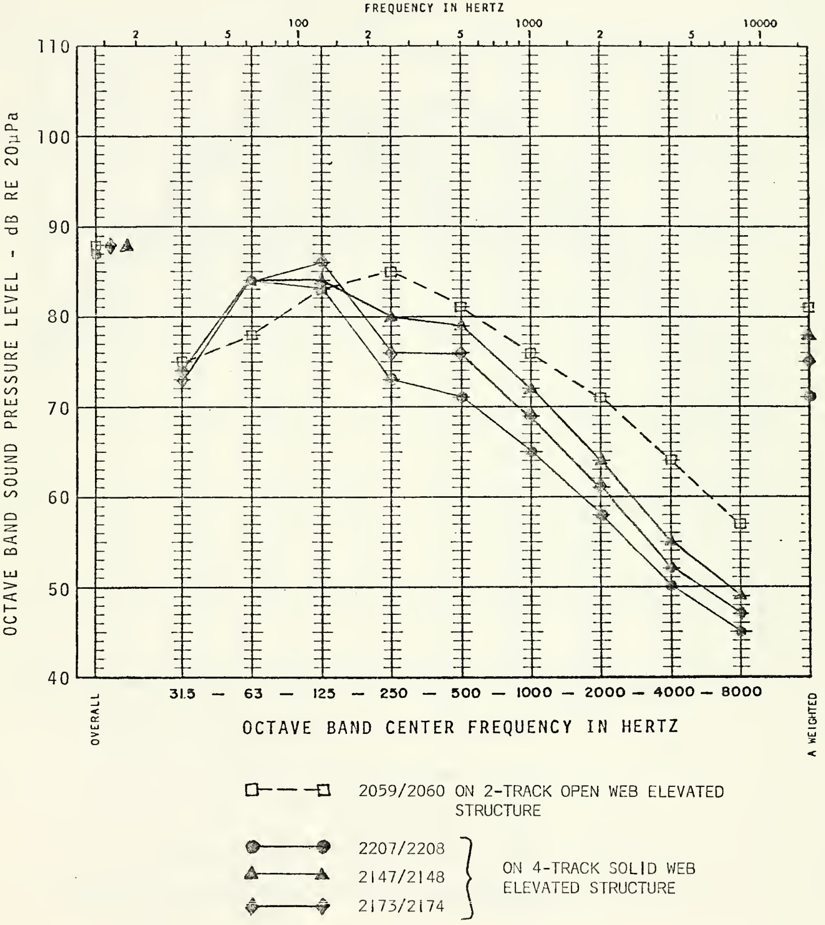


FIGURE A13 WAYSIDE NOISE FROM 2-CAR TRAINS ON ELEVATED STRUCTURE

50 FT FROM TRACK ℄ - 10 MPH

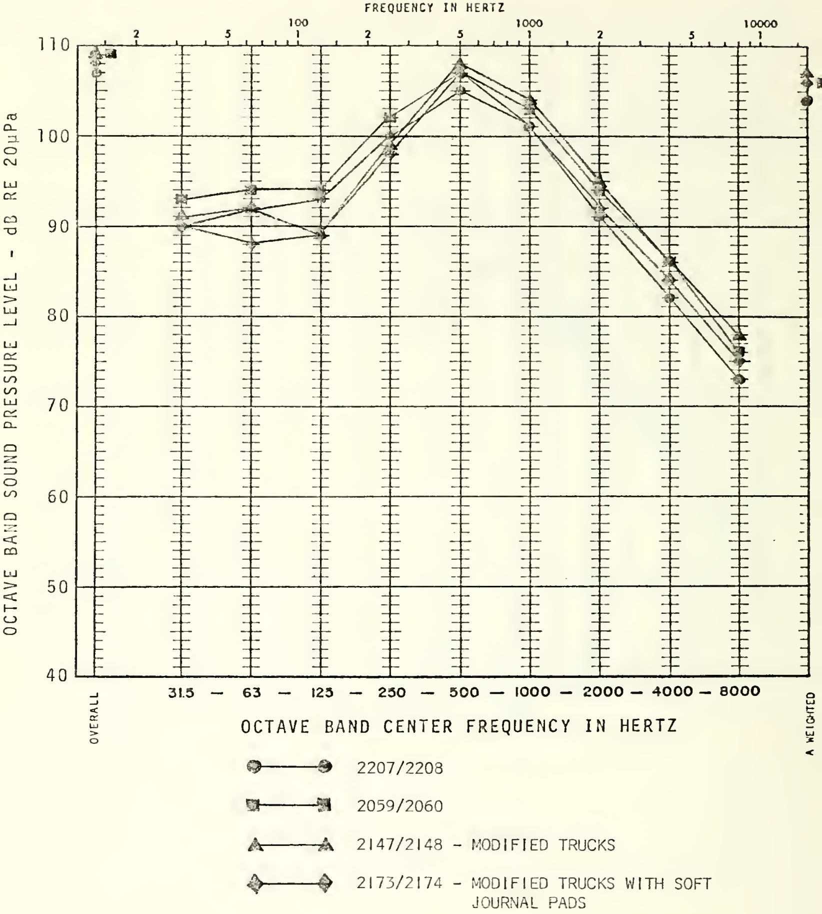


FIGURE A14 WAYSIDE NOISE LEVEL FOR 2-CAR TRAINS ON 4-TRACK SOLID WEB ELEVATED STRUCTURE

25 FT FROM TRACK ℄ - 47 MPH

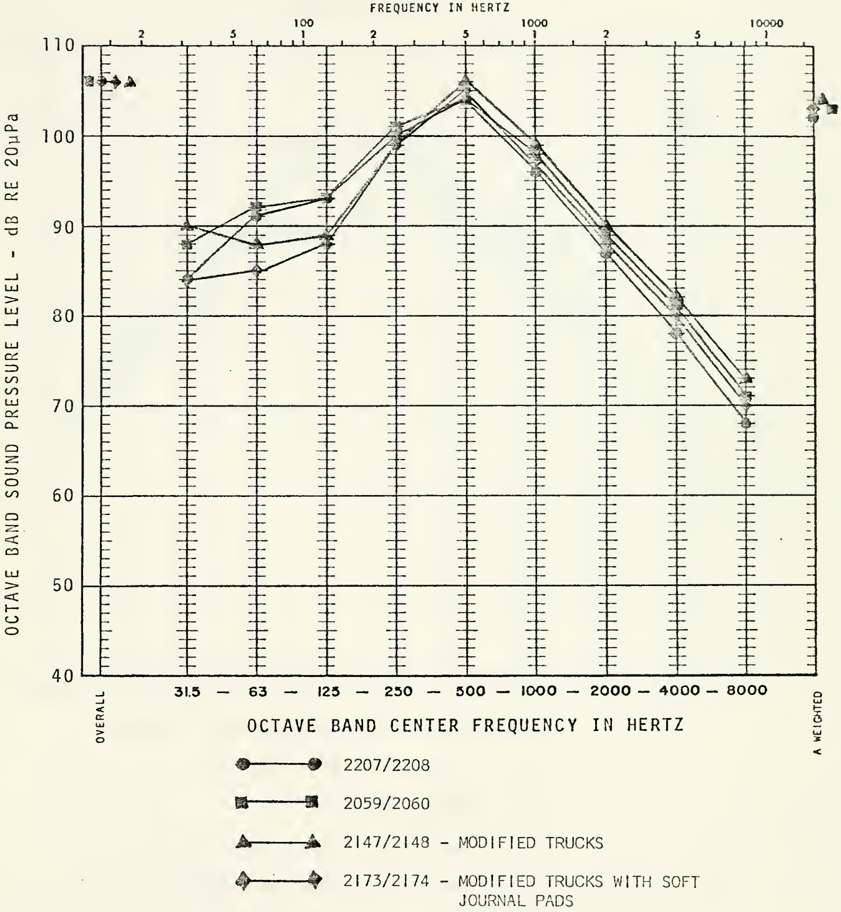


FIGURE A15 WAYSIDE NOISE LEVEL FOR 2-CAR TRAINS ON 4-TRACK SOLID WEB ELEVATED STRUCTURE

25 FT FROM TRACK ℄ - 40 MPH

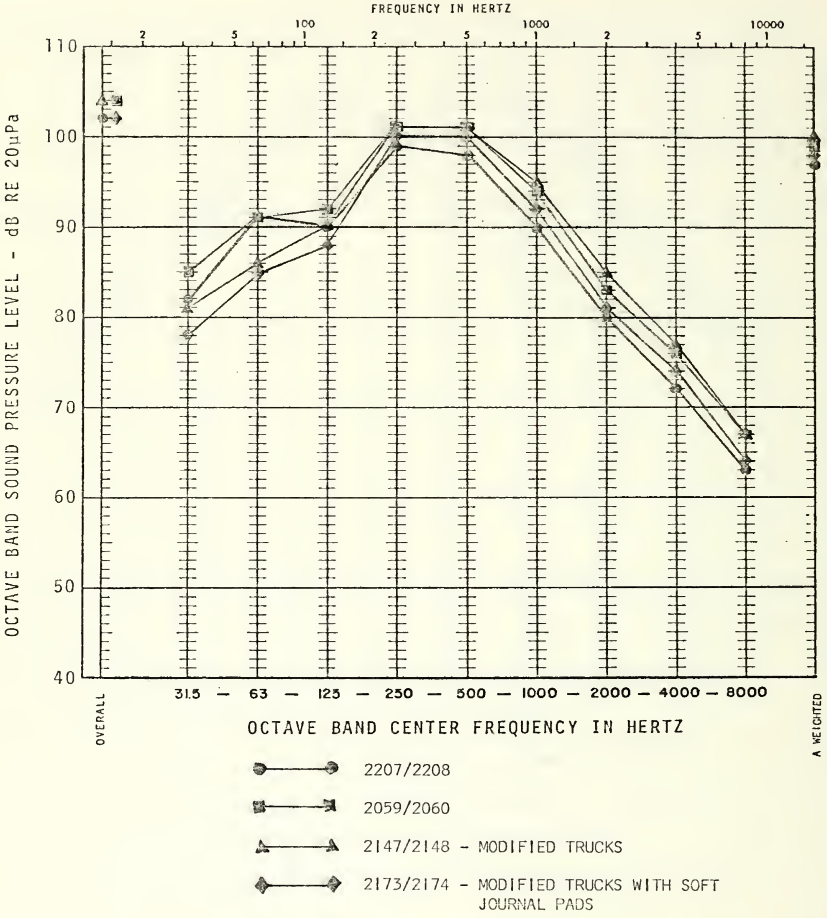


FIGURE A16 WAYSIDE NOISE LEVEL FOR 2-CAR TRAINS ON 4-TRACK SOLID WEB ELEVATED STRUCTURE

25 FT FROM TRACK ℄ - 30 MPH

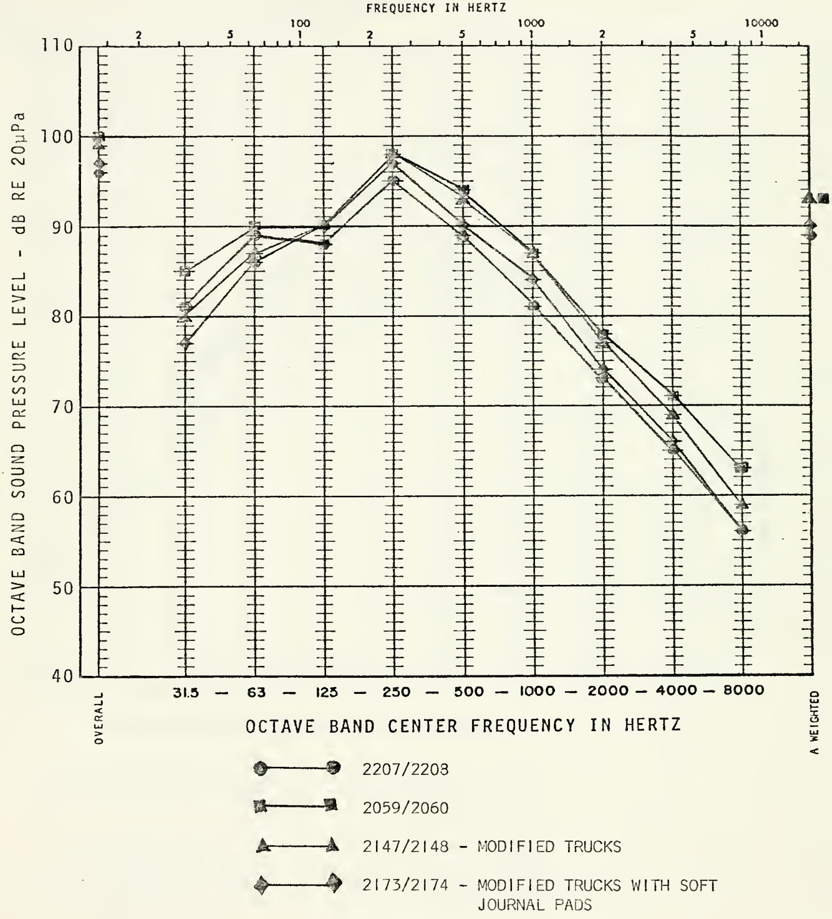


FIGURE A17 WAYSIDE NOISE LEVEL FOR 2-CAR TRAINS ON 4-TRACK SOLID WEB ELEVATED STRUCTURE

25 FT FROM TRACK ℄ - 20 MPH

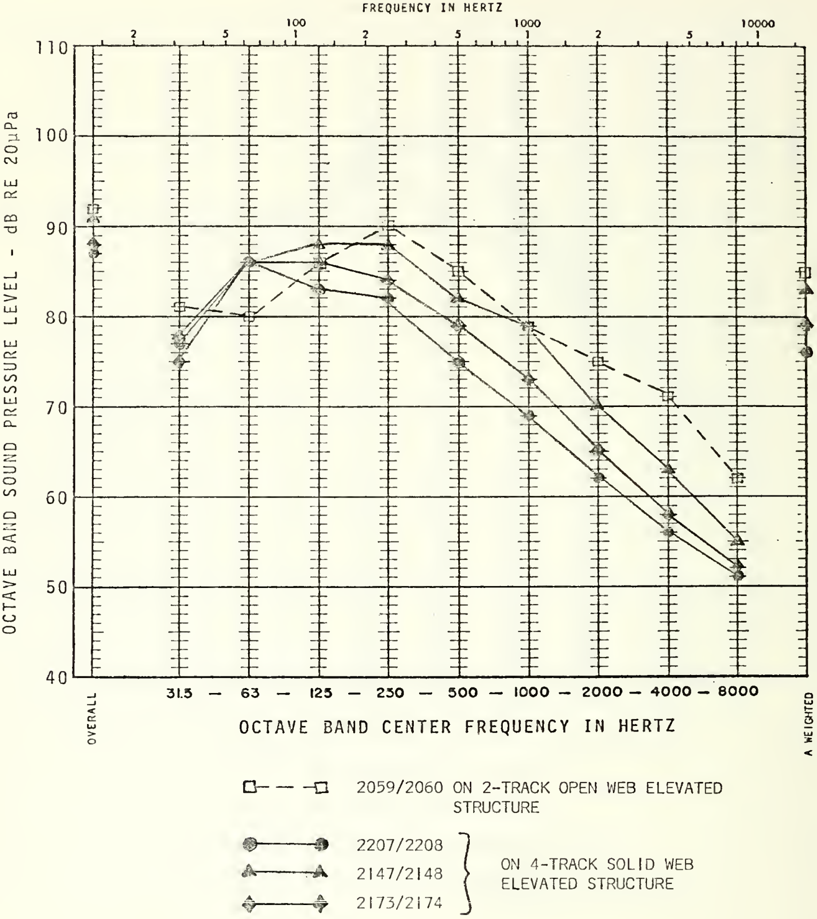


FIGURE A18 WAYSIDE NOISE FROM 2-CAR TRAINS ON ELEVATED STRUCTURE

25 FT FROM TRACK ℄ - 10 MPH

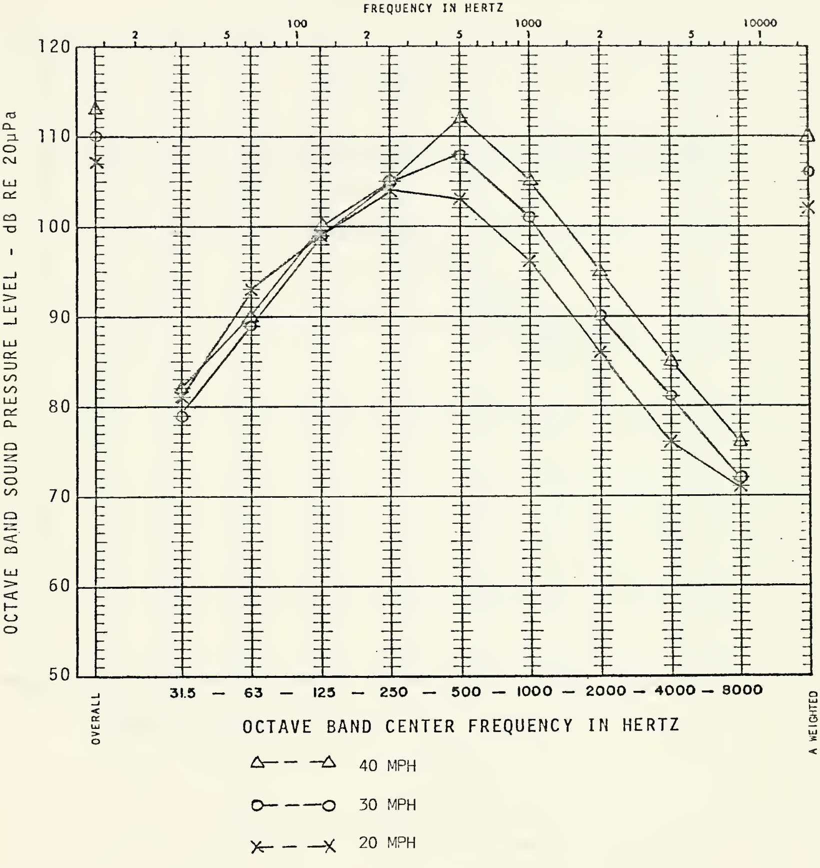


FIGURE A19 NOISE LEVELS DIRECTLY BENEATH THE 4-TRACK SOLID WEB ELEVATED STRUCTURE WITH 2-CAR TRAIN 2059/2060 PASSING BY

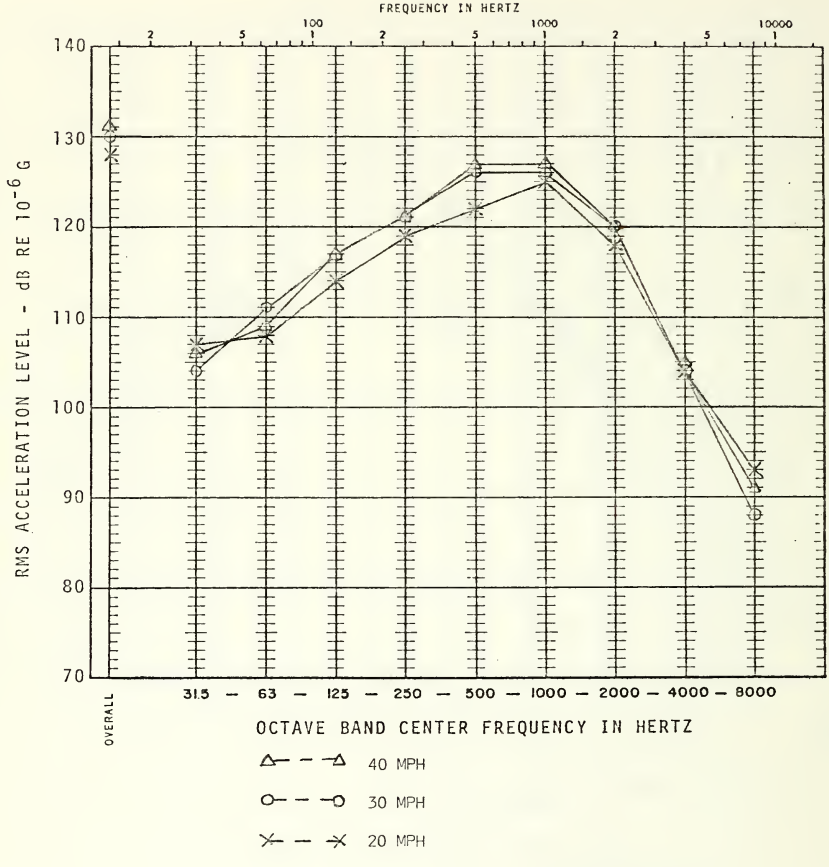


FIGURE A20 VIBRATION LEVELS AT BOTTOM FLANGE OF THE 4-TRACK ELEVATED STRUCTURE WITH 2-CAR TRAIN 2059/2060 PASSING BY

APPENDIX B

WAYSIDE NOISE LEVELS FOR BALLAST AND TIE TRACK OPERATIONS

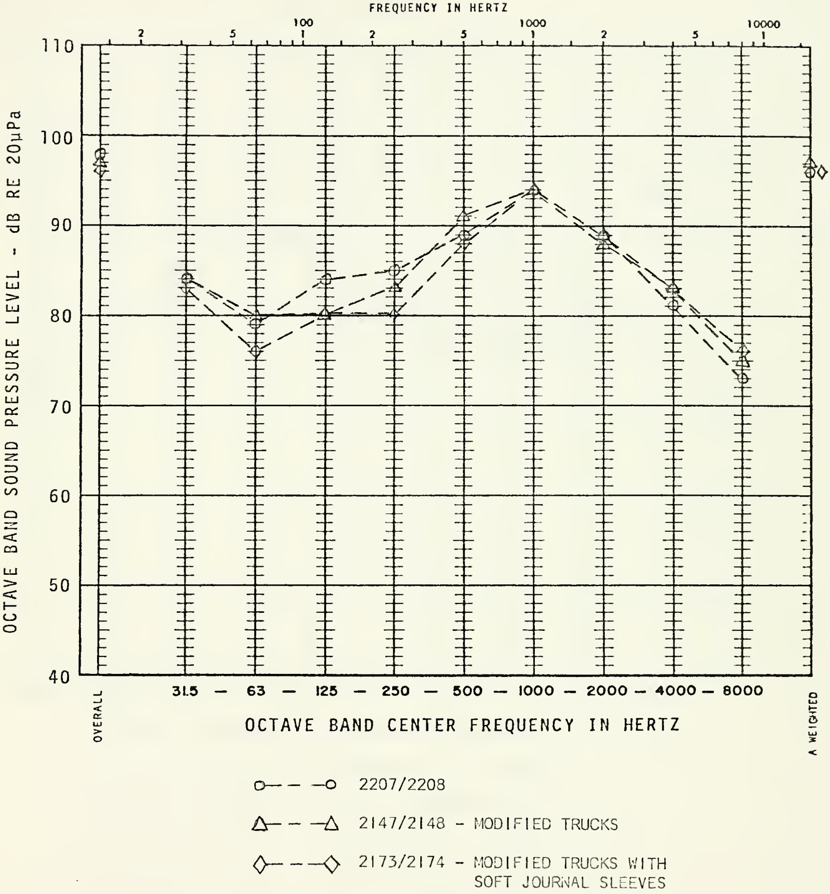


FIGURE B1 WAYSIDE NOISE LEVEL FOR 2-CAR TRAINS ON BALLAST & TIE TRACKS

JOINTED RAIL

50 FT FROM TRACK ℄ - 60 MPH

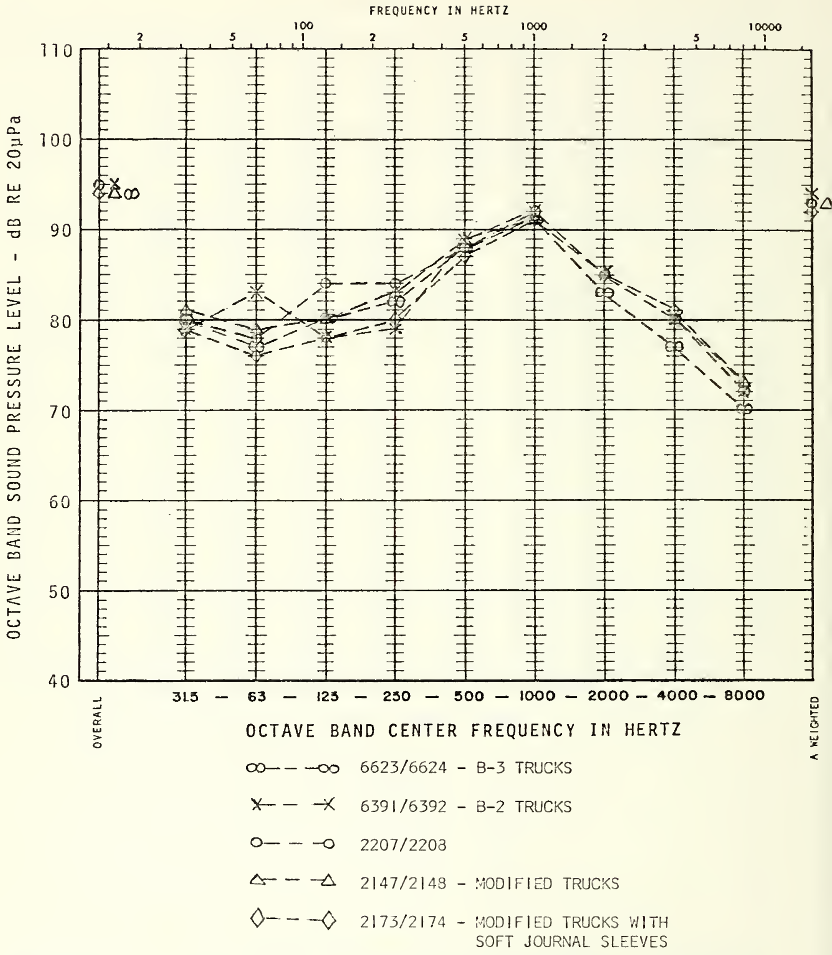


FIGURE B2 WAYSIDE NOISE LEVEL FOR 2-CAR TRAINS ON BALLAST & TIE TRACKS

JOINTED RAIL

50 FT FROM TRACK ℄ - 50 MPH

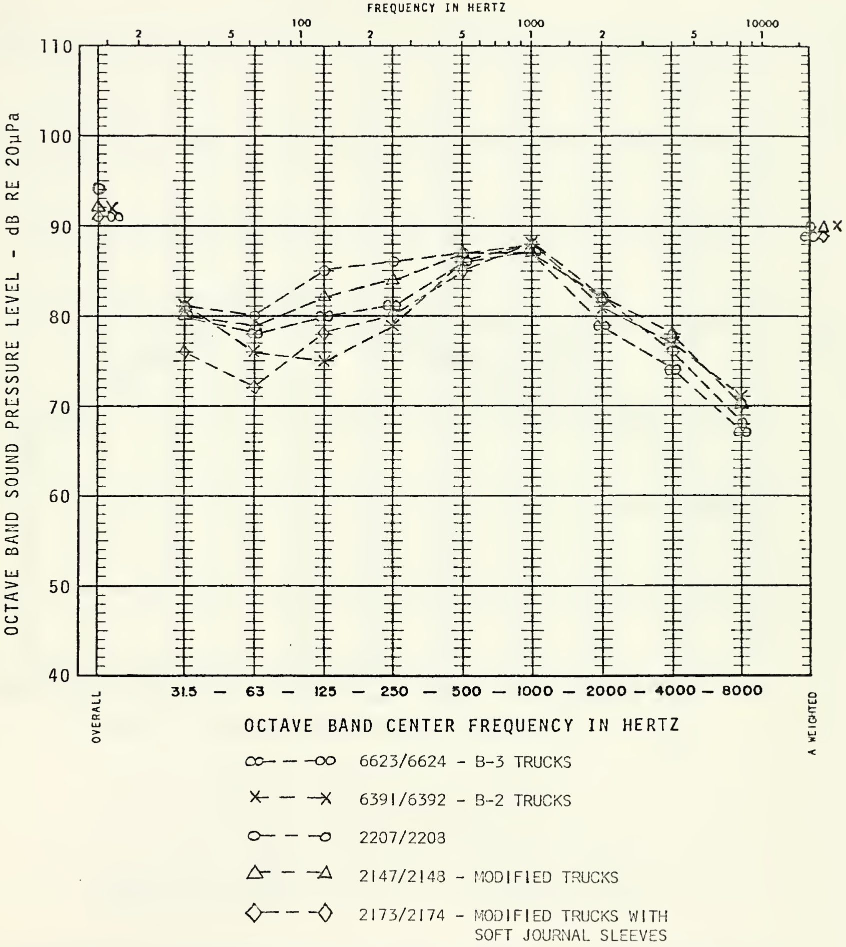


FIGURE B 3 WAYSIDE NOISE LEVEL FOR 2-CAR TRAINS ON BALLAST & TIE TRACKS

JOINTED RAIL

50 FT FROM TRACK ℄ - 40 MPH

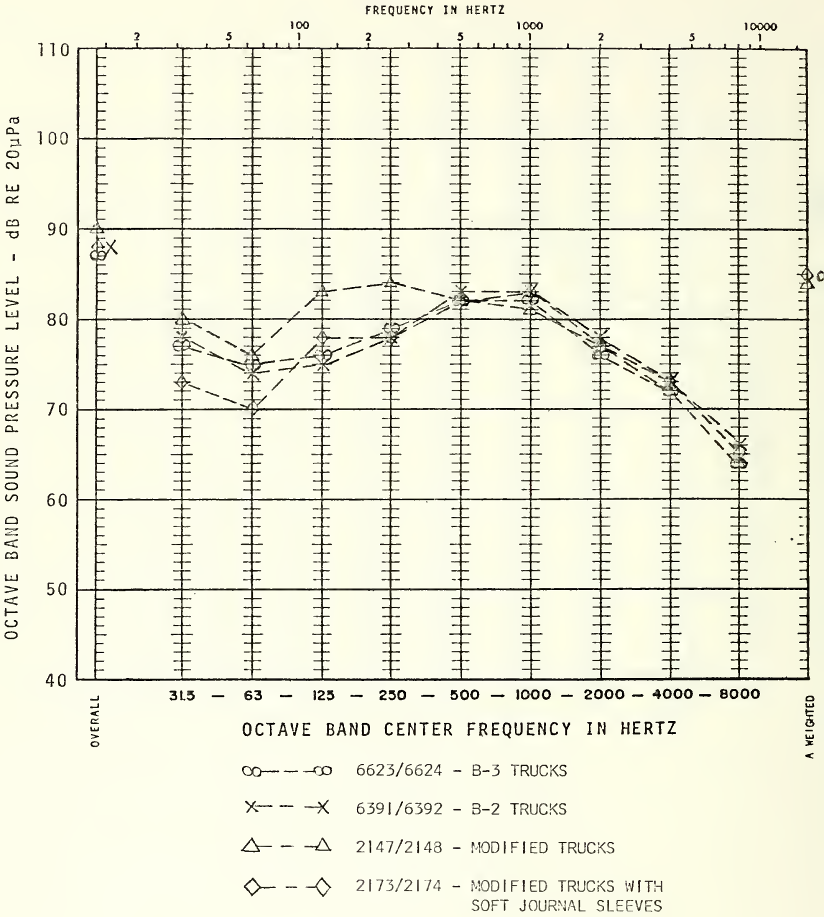


FIGURE B4 WAYSIDE NOISE LEVEL FOR 2-CAR TRAINS ON BALLAST & TIE TRACKS

JOINTED RAIL

50 FT FROM TRACK ℄ - 30 MPH

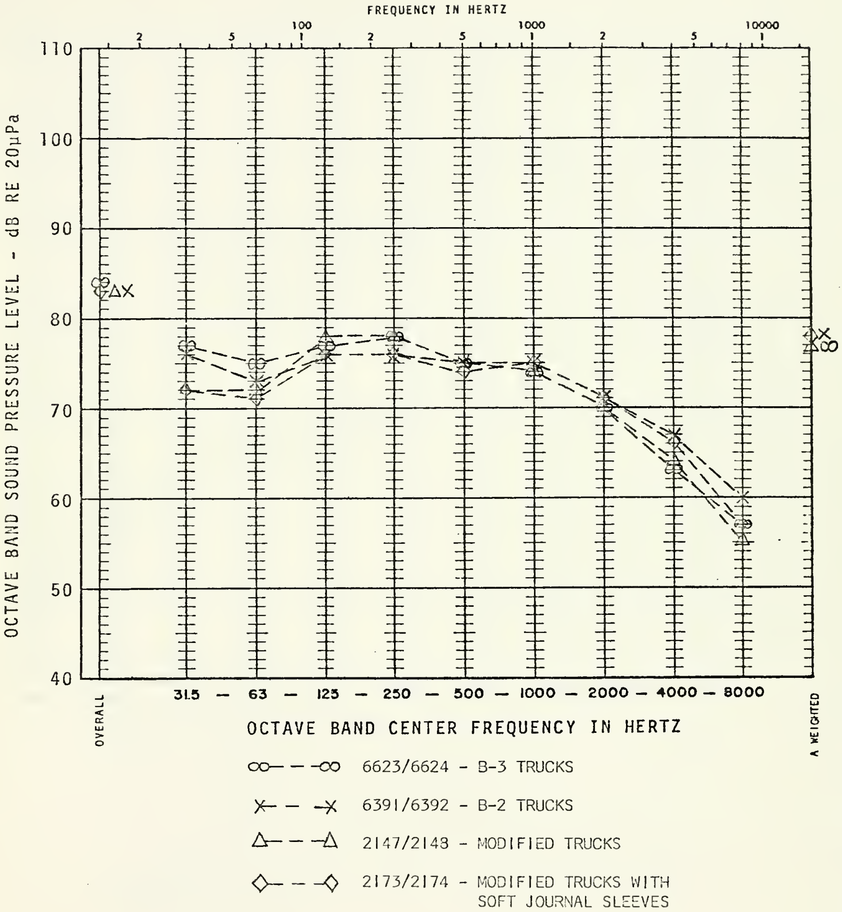


FIGURE B5 WAYSIDE NOISE LEVEL FOR 2-CAR TRAINS ON BALLAST & TIE TRACKS

JOINTED RAIL

50 FT FROM TRACK ℄ - 20 MPH

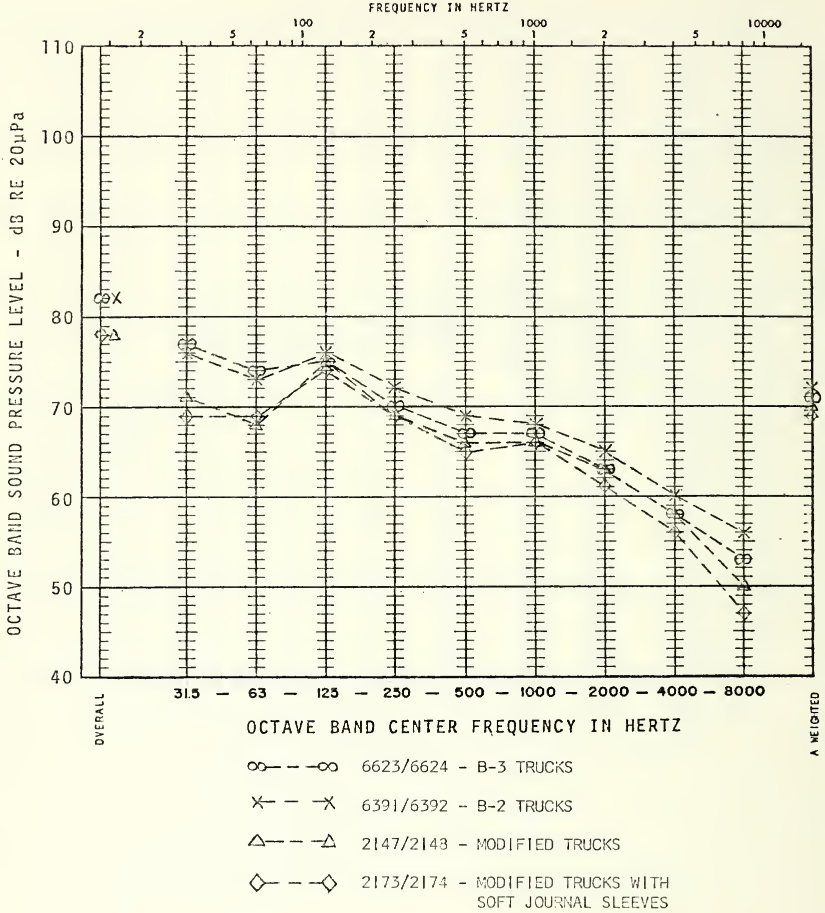


FIGURE B 6 WAYSIDE NOISE LEVEL FOR 2-CAR TRAINS ON BALLAST & TIE TRACKS

JOINTED RAIL

50 FT FROM TRACK ℄ - 10 MPH

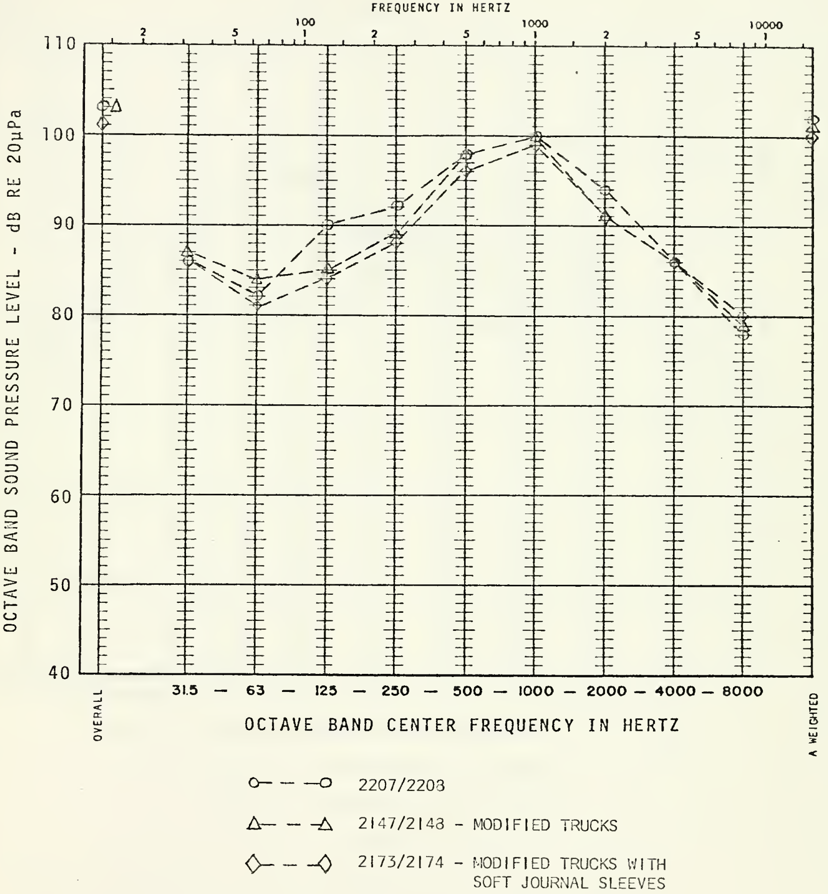


FIGURE B7 WAYSIDE NOISE LEVEL FOR 2-CAR TRAINS ON BALLAST & TIE TRACKS

JOINTED RAIL

25 FT FROM TRACK ℄ - 60 MPH

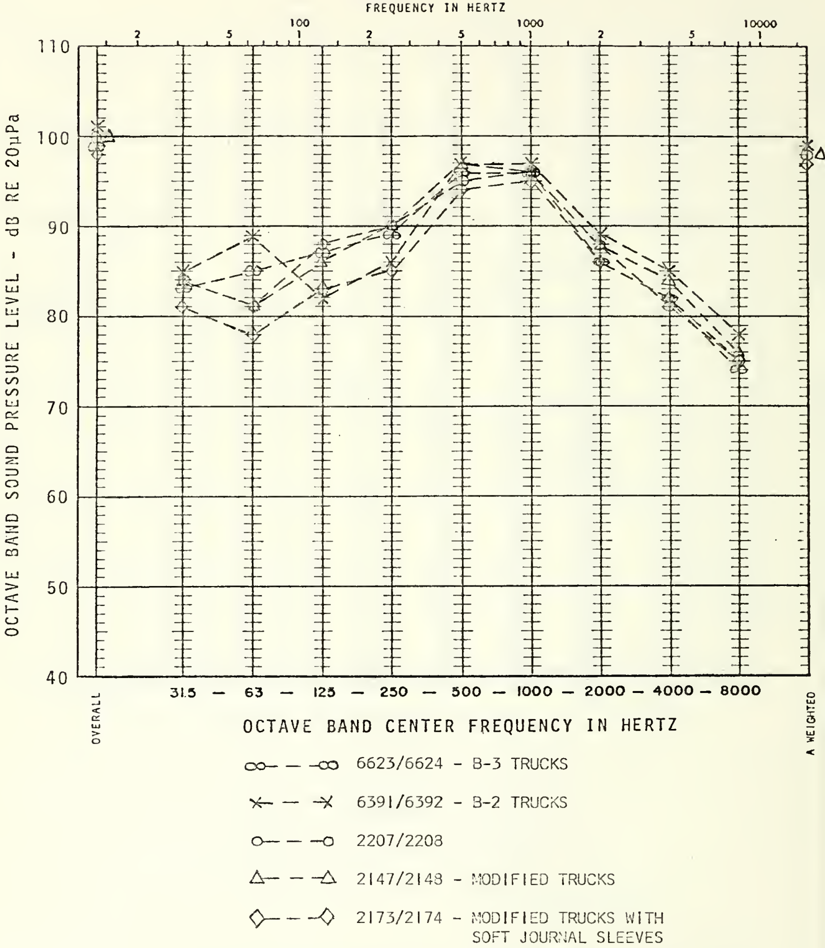


FIGURE B8 WAYSIDE NOISE LEVEL FOR 2-CAR TRAINS ON BALLAST & TIE TRACKS

JOINTED RAIL

25 FT FROM TRACK ℄ - 50 MPH

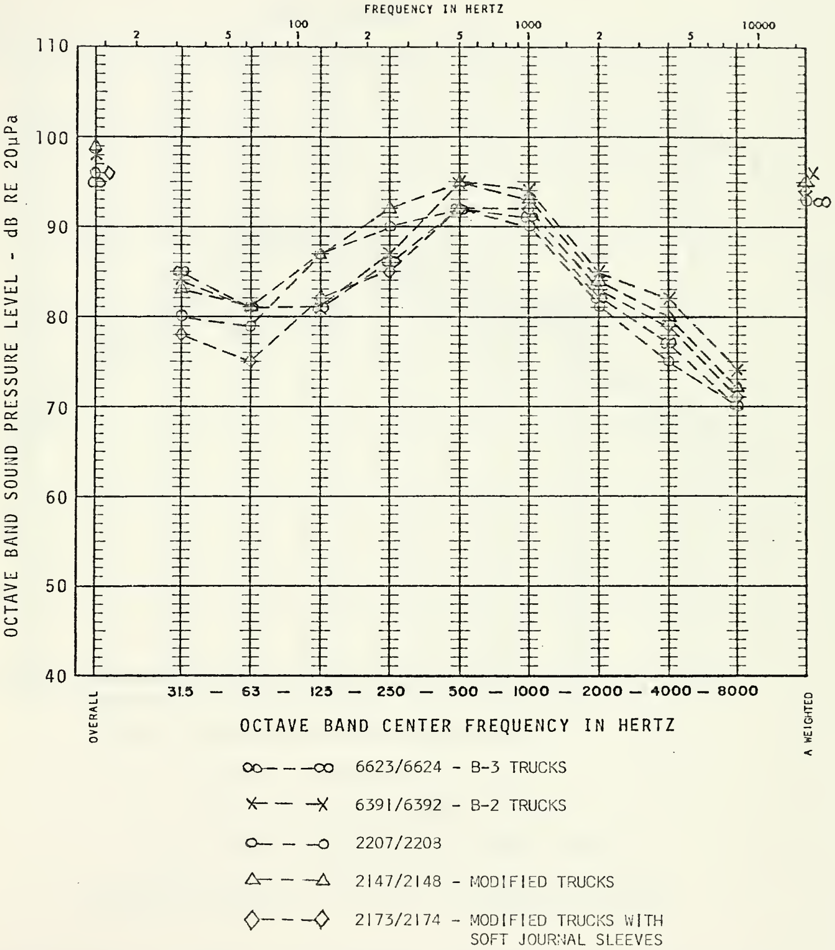


FIGURE B9 WAYSIDE NOISE LEVEL FOR 2-CAR TRAINS ON BALLAST & TIE TRACKS

JOINTED RAIL

25 FT FROM TRACK ℄ - 40 MPH

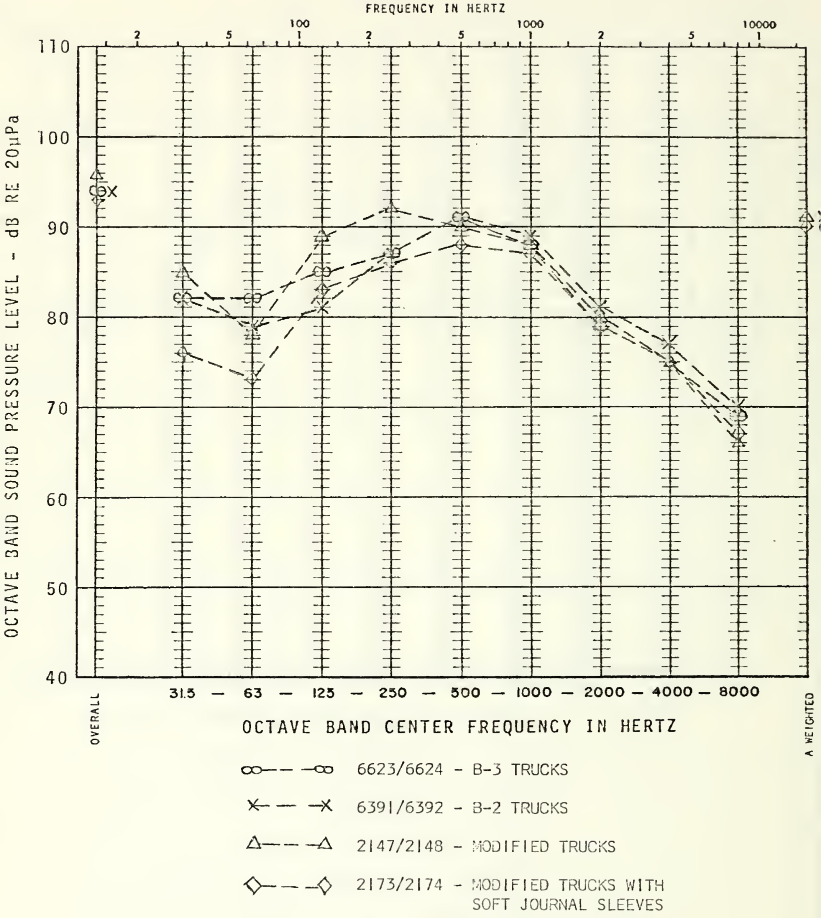


FIGURE B10 WAYSIDE NOISE LEVEL FOR 2-CAR TRAINS ON BALLAST & TIE TRACKS

JOINTED RAIL

25 FT FROM TRACK ℄ - 30 MPH

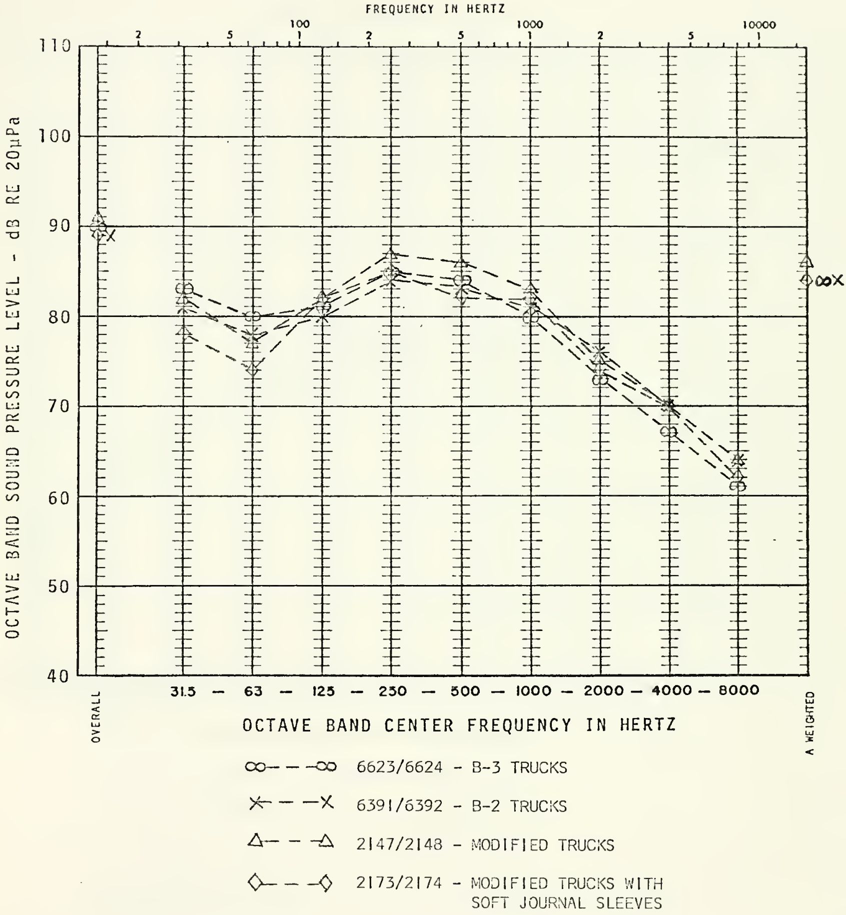


FIGURE B 11 WAYSIDE NOISE LEVEL FOR 2-CAR TRAINS ON BALLAST & TIE TRACKS

JOINTED RAIL

25 FT FROM TRACK ¢ - 20 MPH

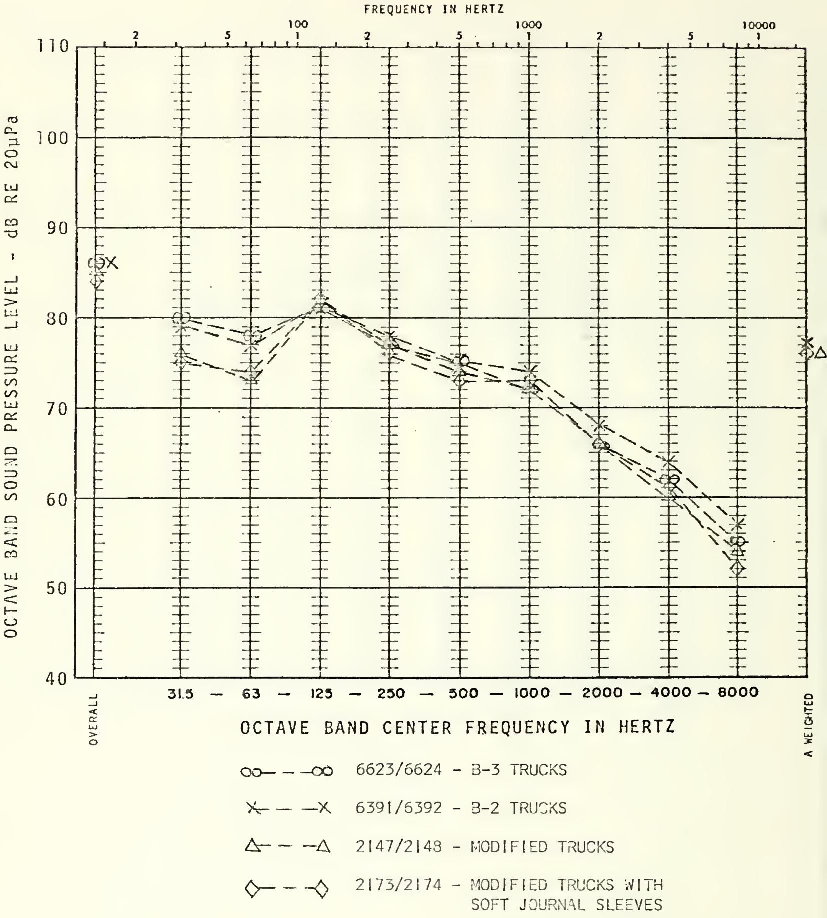


FIGURE B12 WAYSIDE NOISE LEVEL FOR 2-CAR TRAINS ON BALLAST & TIE TRACKS

JOINTED RAIL

25 FT FROM TRACK ℄ - 10 MPH

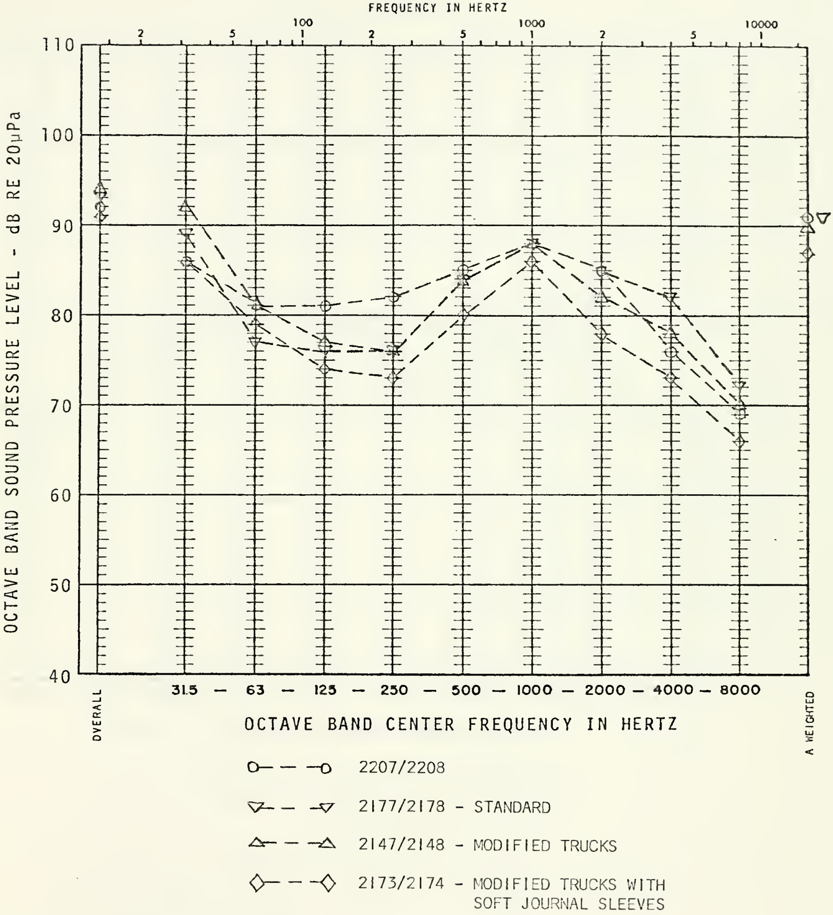


FIGURE B13 WAYSIDE NOISE LEVEL FOR 2-CAR TRAINS ON BALLAST & TIE TRACKS

WORN CONTINUOUS WELDED RAIL - BEFORE SMOOTHING

50 FT FROM TRACK ℄ - 60 MPH

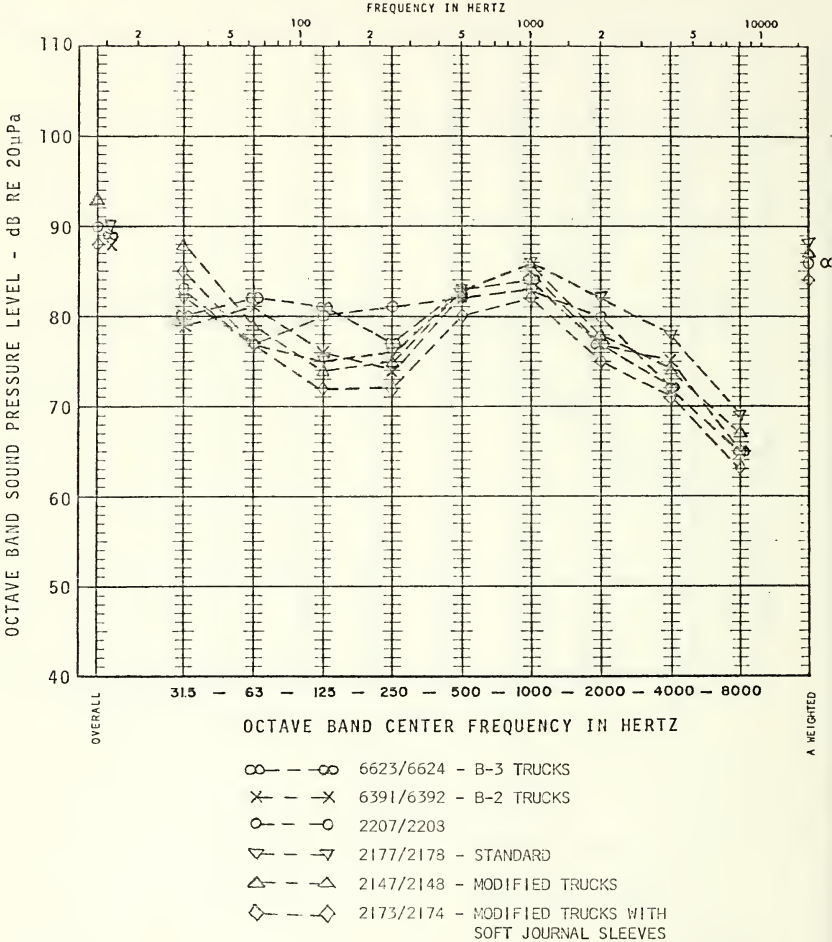


FIGURE B14 WAYSIDE NOISE LEVEL FOR 2-CAR TRAINS ON BALLAST & TIE TRACKS

WORN CONTINUOUS WELDED RAIL - BEFORE SMOOTHING

50 FT FROM TRACK ℄ - 50 MPH

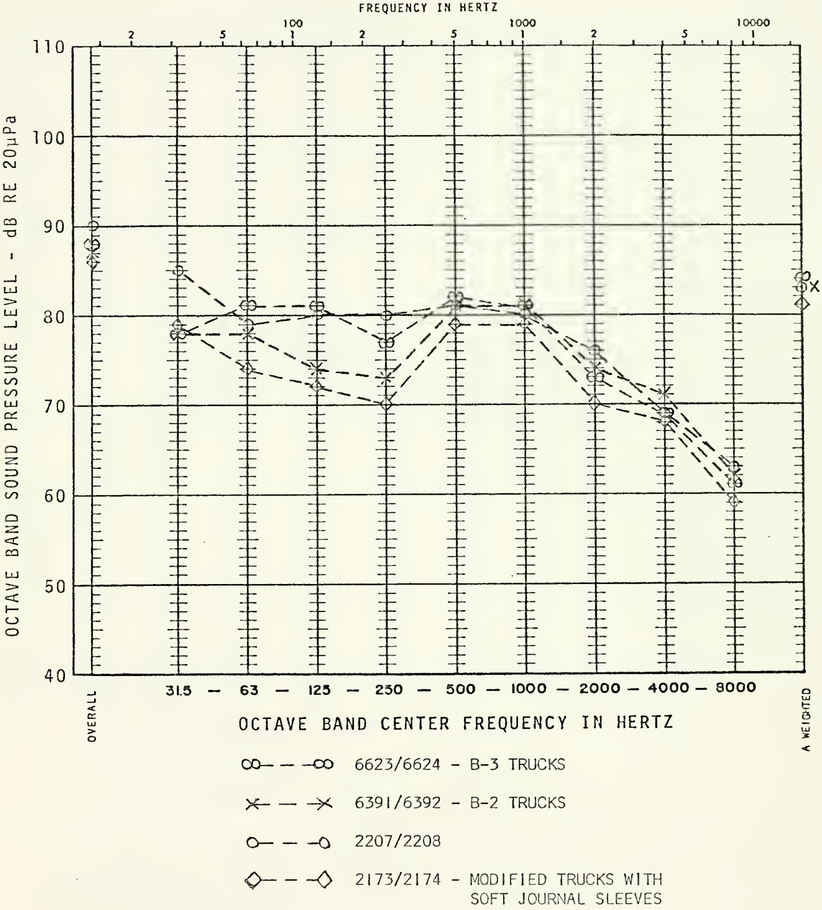
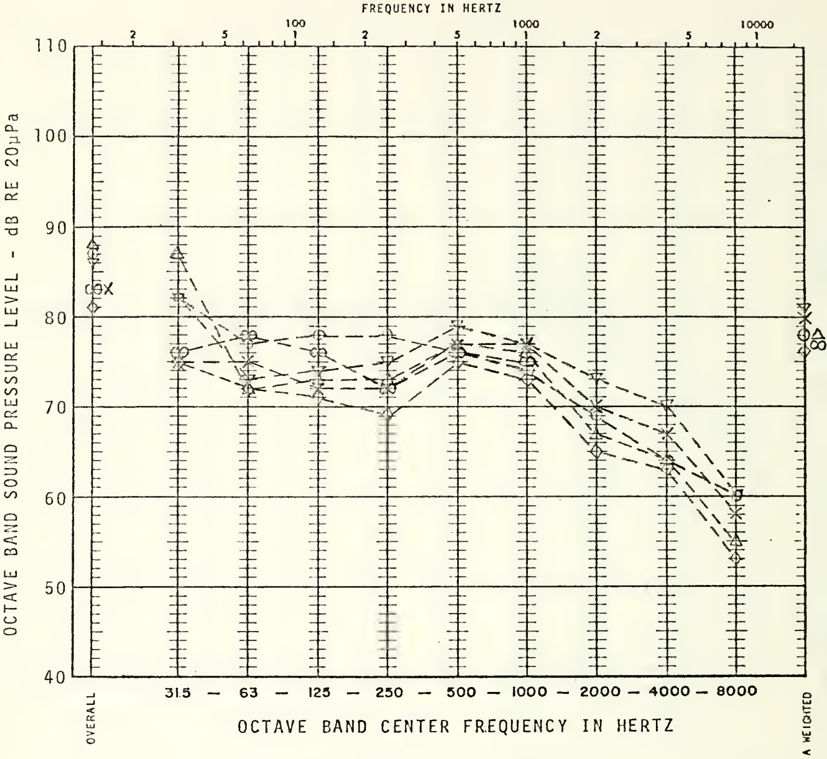


FIGURE B15 WAYSIDE NOISE LEVEL FOR 2-CAR TRAINS ON BALLAST & TIE TRACKS

WORN CONTINUOUS WELDED RAIL - BEFORE SMOOTHING

50 FT FROM TRACK ℄ - 40 MPH



ꝏ— — —ꝏ	6623/6624 - B-3 TRUCKS
X— — —X	6391/6392 - B-2 TRUCKS
O— — —O	2207/2208
▽— — —▽	2177/2178 - STANDARD
△— — —△	2147/2148 - MODIFIED TRUCKS
◇— — —◇	2173/2174 - MODIFIED TRUCKS WITH SOFT JOURNAL SLEEVES

FIGURE B16 WAYSIDE NOISE LEVEL FOR 2-CAR TRAINS ON BALLAST & TIE TRACKS

WORN CONTINUOUS WELDED RAIL - BEFORE SMOOTHING

50 FT FROM TRACK ℄ - 30 MPH

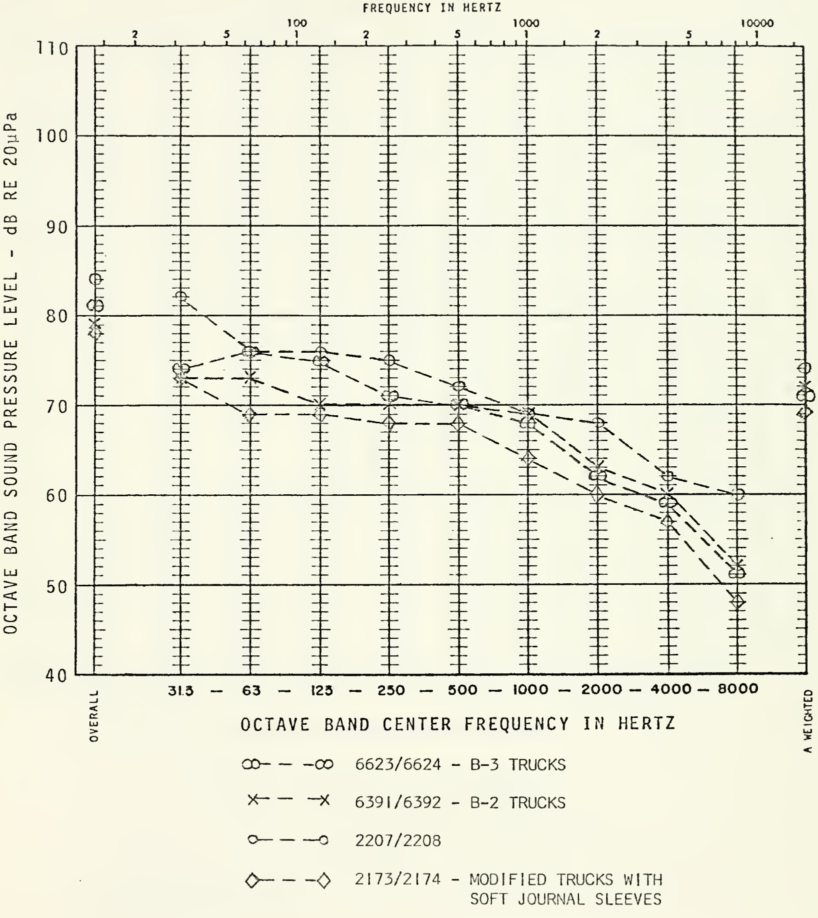


FIGURE B17 WAYSIDE NOISE LEVEL FOR 2-CAR TRAINS ON BALLAST & TIE TRACKS

WORN CONTINUOUS WELDED RAIL - BEFORE SMOOTHING

50 FT FROM TRACK ℄ - 20 MPH

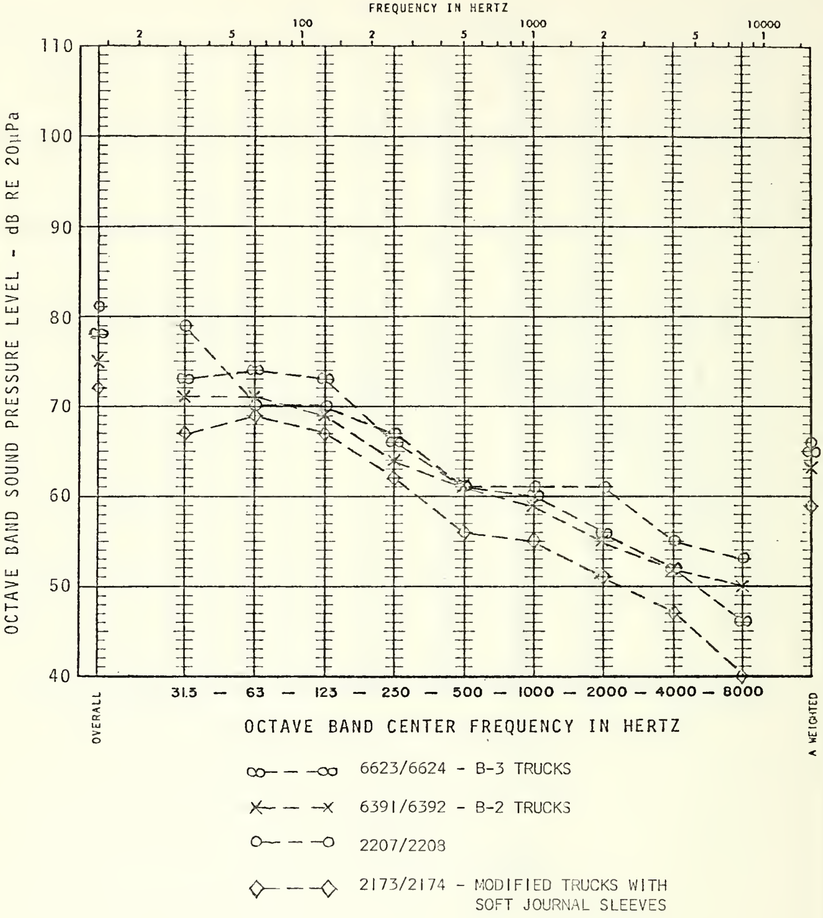


FIGURE B18 WAYSIDE NOISE LEVEL FOR 2-CAR TRAINS ON BALLAST & TIE TRACKS

WORN CONTINUOUS WELDED RAIL - BEFORE SMOOTHING

50 FT FROM TRACK ℄ - 10 MPH

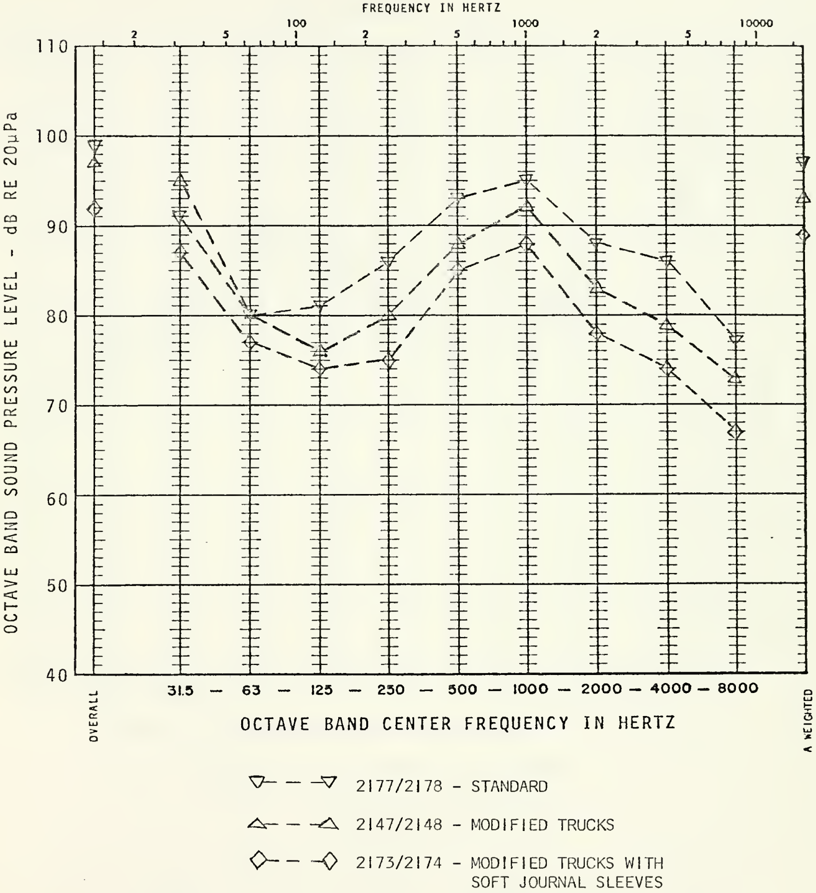


FIGURE B19 WAYSIDE NOISE LEVEL FOR 2-CAR TRAINS ON BALLAST & TIE TRACKS

WORN CONTINUOUS WELDED RAIL - BEFORE SMOOTHING

25 FT FROM TRACK ℄ - 60 MPH

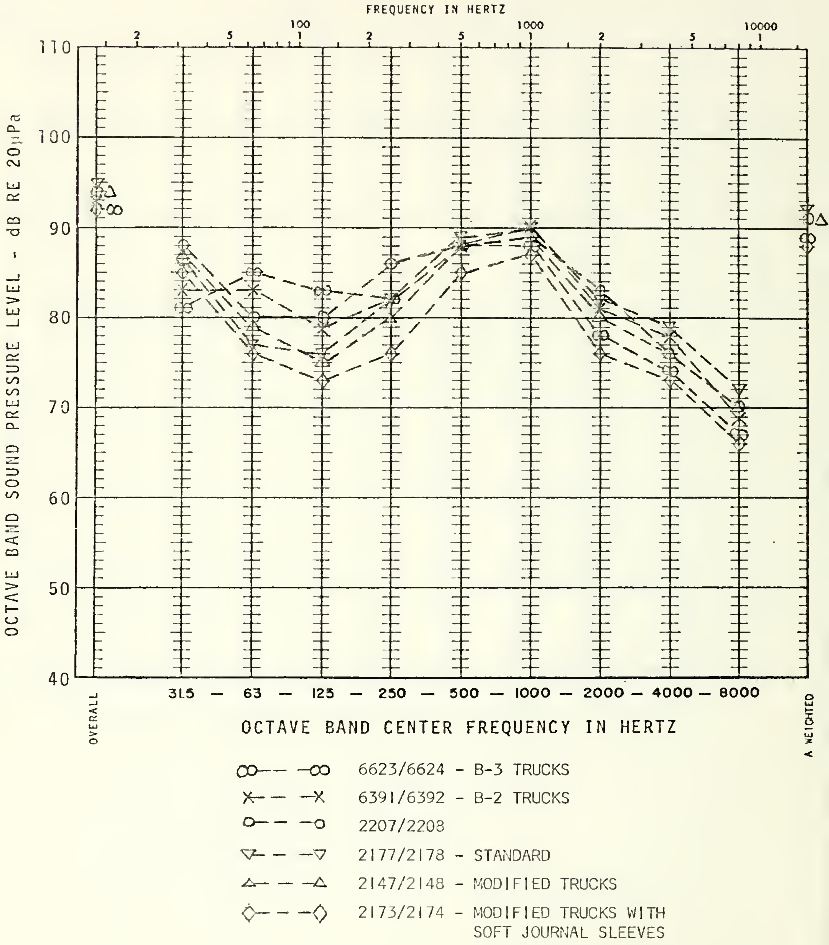


FIGURE B20 WAYSIDE NOISE LEVEL FOR 2-CAR TRAINS ON BALLAST & TIE TRACKS

WORN CONTINUOUS WELDED RAIL - BEFORE SMOOTHING

25 FT FROM TRACK ℄ - 50 MPH

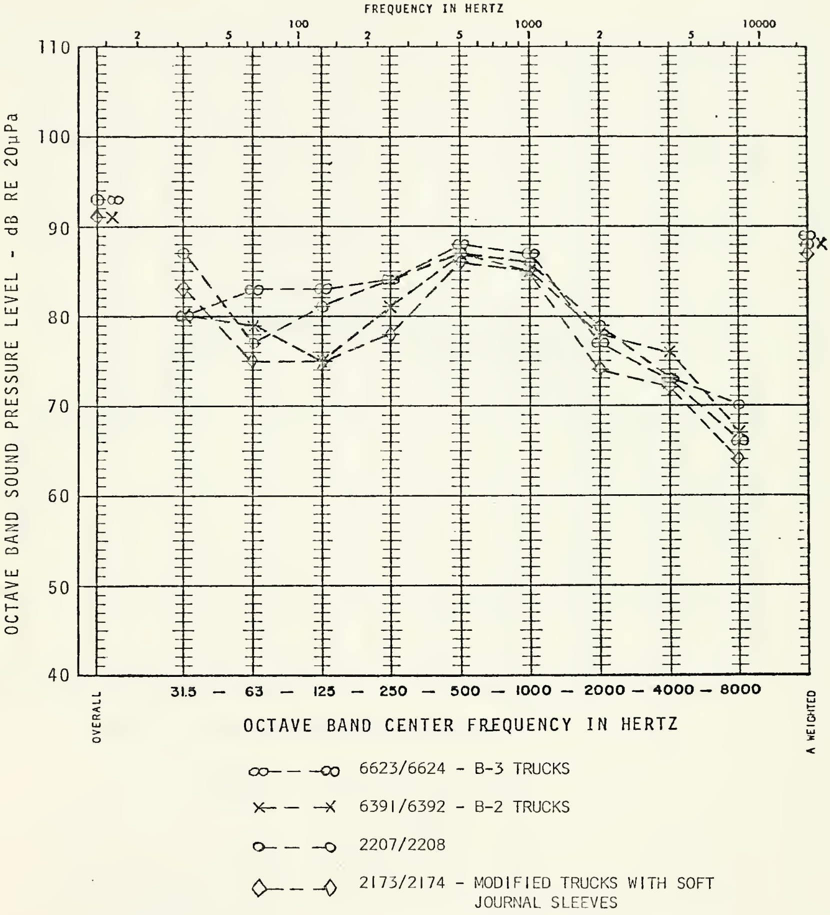


FIGURE B21 WAYSIDE NOISE LEVEL FOR 2-CAR TRAINS ON BALLAST & TIE TRACKS

WORN CONTINUOUS WELDED RAIL - BEFORE SMOOTHING

25 FT FROM TRACK ℄ - 40 MPH

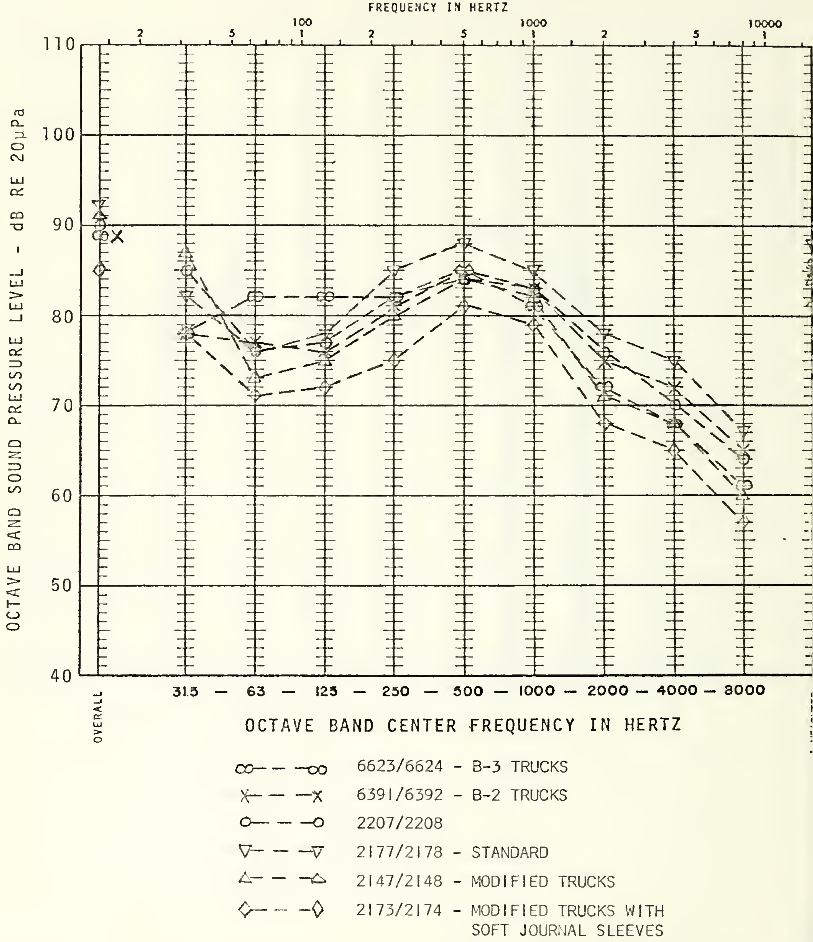


FIGURE B22 WAYSIDE NOISE LEVEL FOR 2-CAR TRAINS ON BALLAST & TIE TRACKS

WORN CONTINUOUS WELDED RAIL - BEFORE SMOOTHING

25 FT FROM TRACK ℄ - 30 MPH

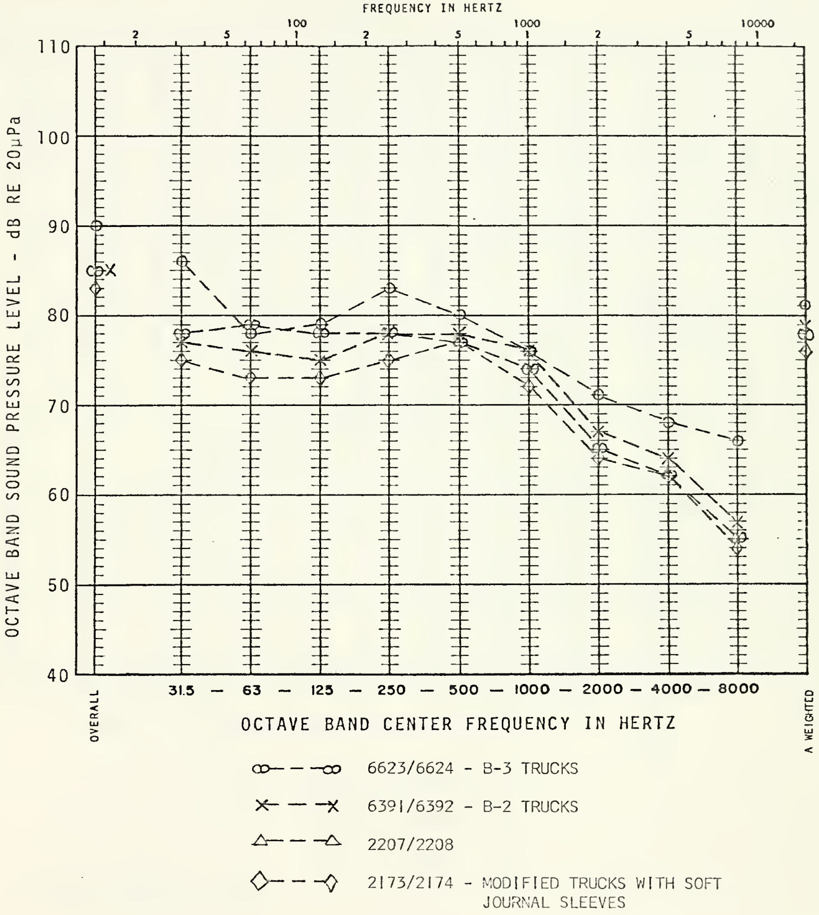


FIGURE B23 WAYSIDE NOISE LEVEL FOR 2-CAR TRAINS ON BALLAST & TIE TRACKS

WORN CONTINUOUS WELDED RAIL - BEFORE SMOOTHING

25 FT FROM TRACK ℄ - 20 MPH

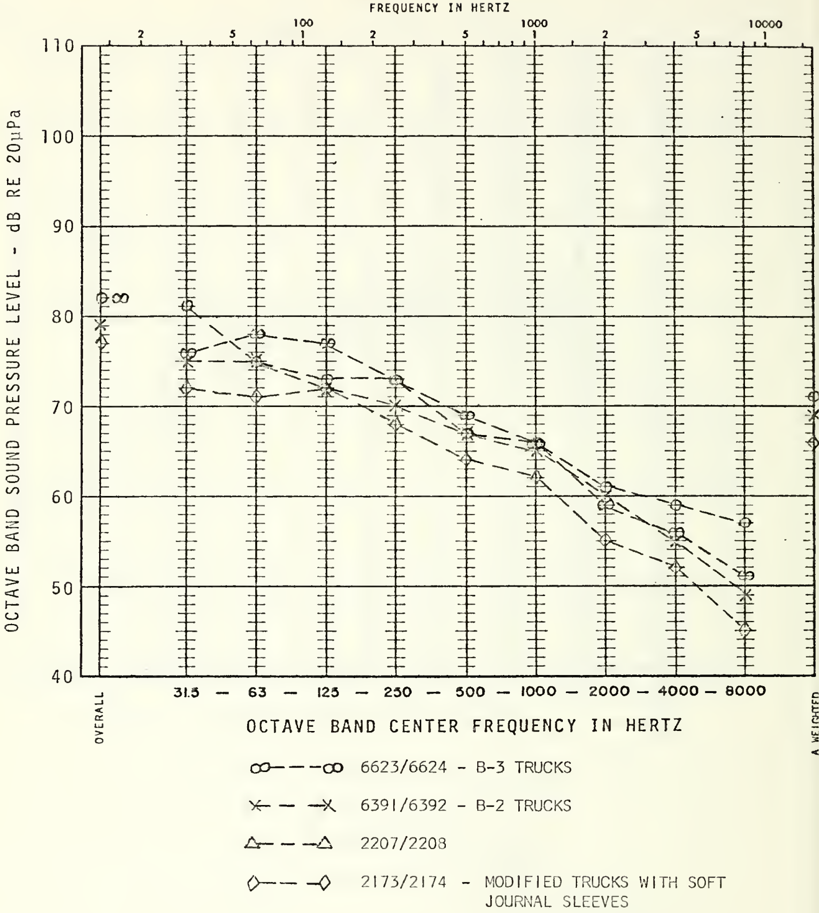


FIGURE B24 WAYSIDE NOISE LEVEL FOR 2-CAR TRAINS ON BALLAST & TIE TRACKS

WORN CONTINUOUS WELDED RAIL - BEFORE SMOOTHING

25 FT FROM TRACK ℄ - 10 MPH

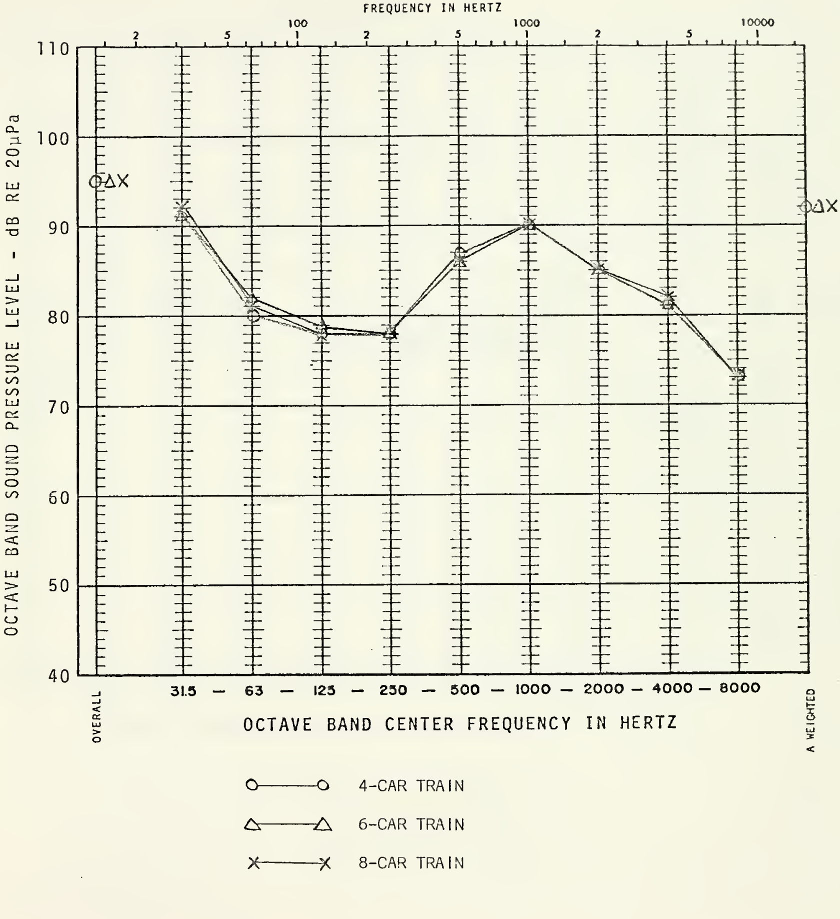


FIGURE B 25 WAYSIDE NOISE LEVEL FOR LONG 2000 SERIES TRAINS

WORN CONTINUOUS WELDED RAIL - BEFORE SMOOTHING
50 FT FROM TRACK ℄ - 60 MPH

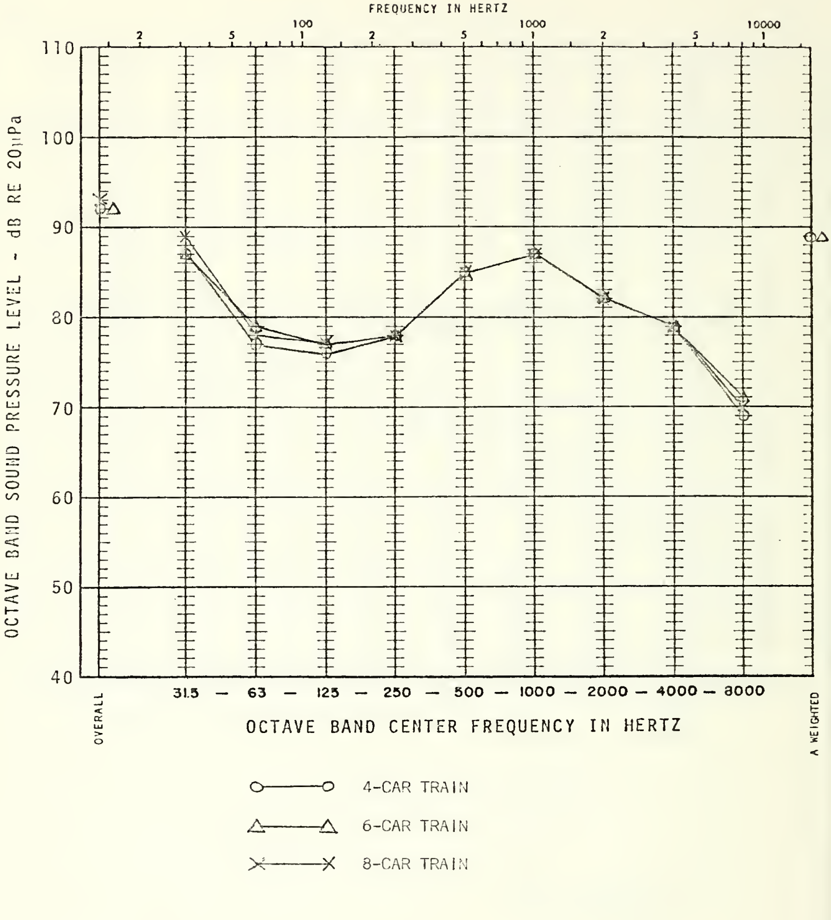


FIGURE B26 WAYSIDE NOISE LEVEL FOR LONG 2000 SERIES TRAINS

WORN CONTINUOUS WELDED RAIL - BEFORE SMOOTHING
50 FT FROM TRACK ¢ - 50 MPH

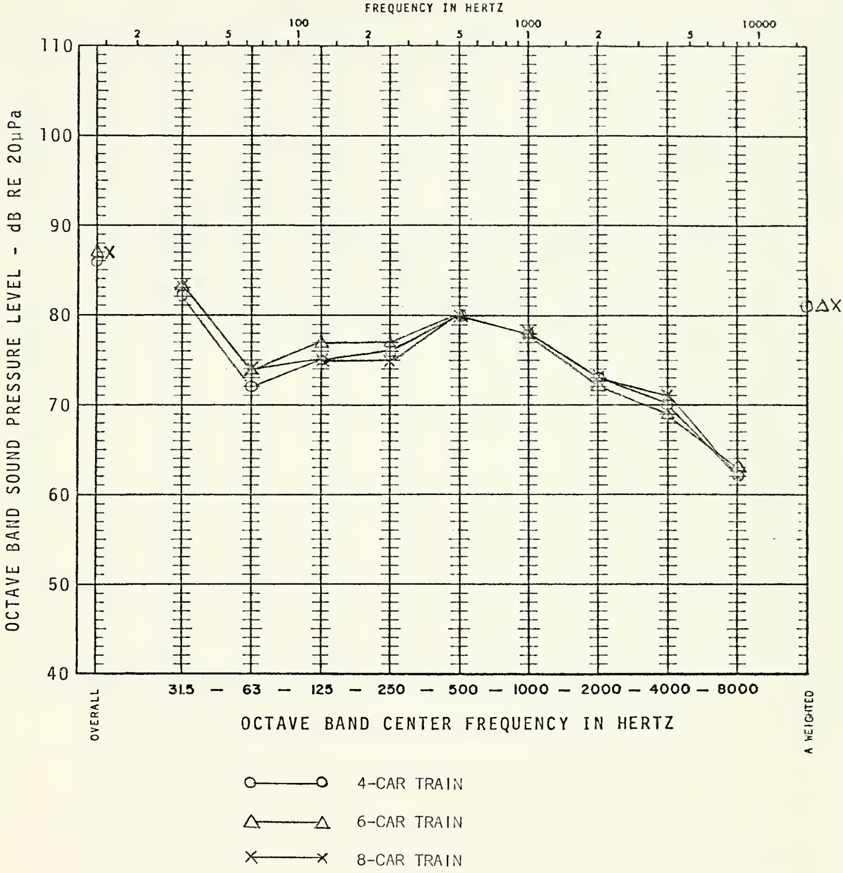


FIGURE B 27 WAYSIDE NOISE LEVEL FOR LONG 2000 SERIES TRAINS

WORN CONTINUOUS WELDED RAIL - BEFORE SMOOTHING
50 FT FROM TRACK ℄ - 30 MPH

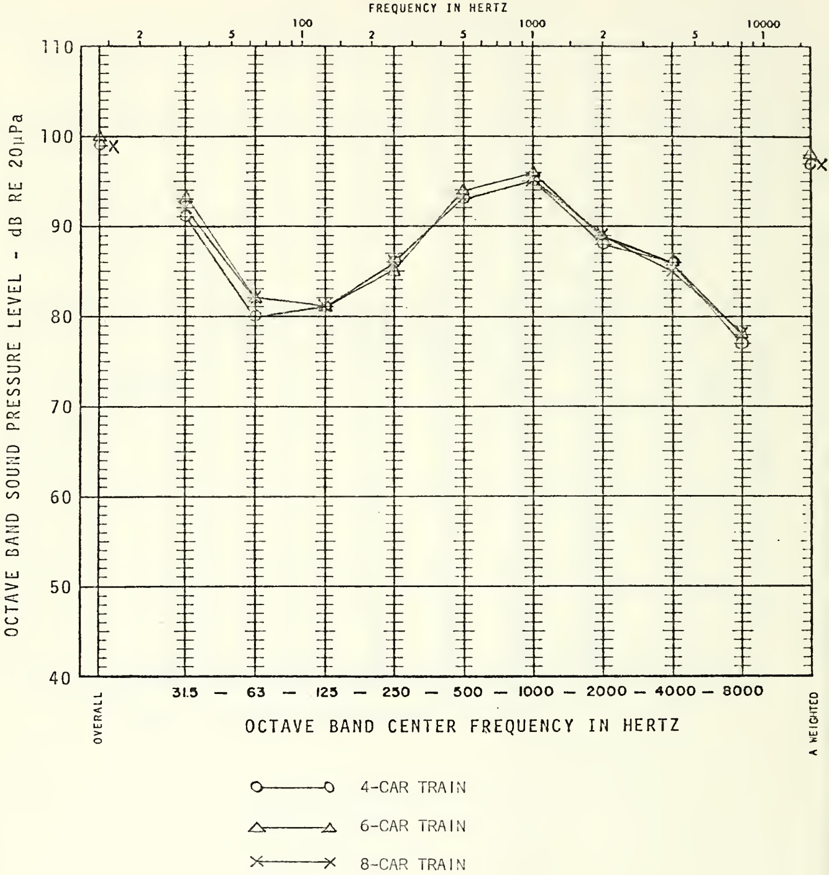


FIGURE B28 WAYSIDE NOISE LEVEL FOR LONG 2000 SERIES TRAINS

WORN CONTINUOUS WELDED RAIL - BEFORE SMOOTHING
25 FT FROM TRACK ℄ - 60 MPH

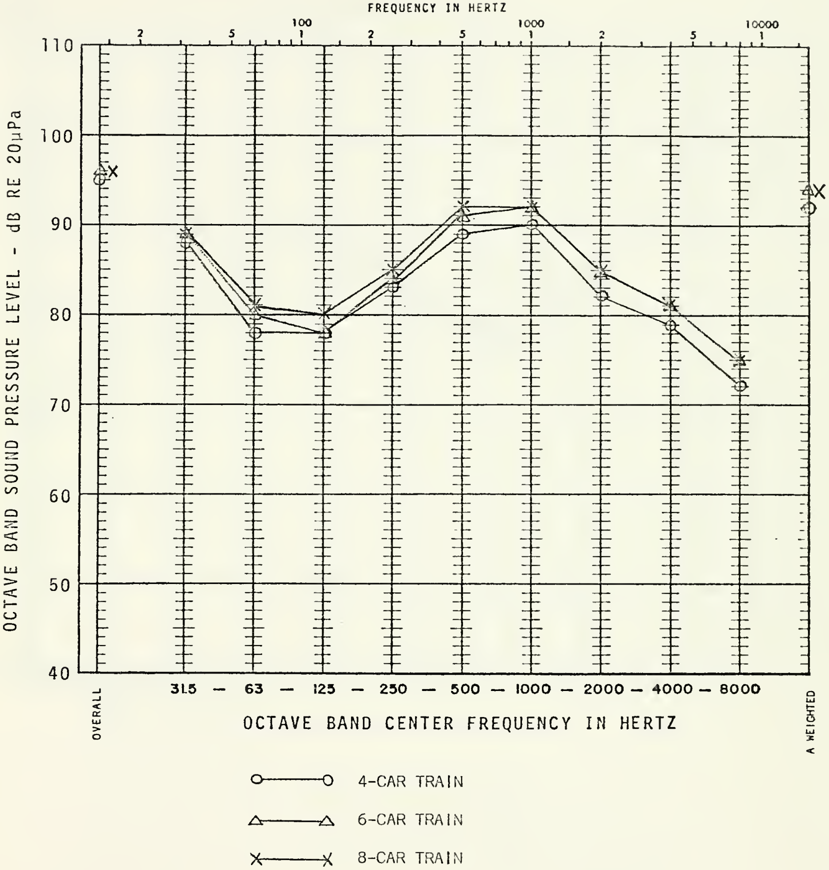


FIGURE B29 WAYSIDE NOISE LEVEL FOR LONG 2000 SERIES TRAINS

WORN CONTINUOUS WELDED RAIL - BEFORE SMOOTHING
25 FT FROM TRACK ℄ - 50 MPH

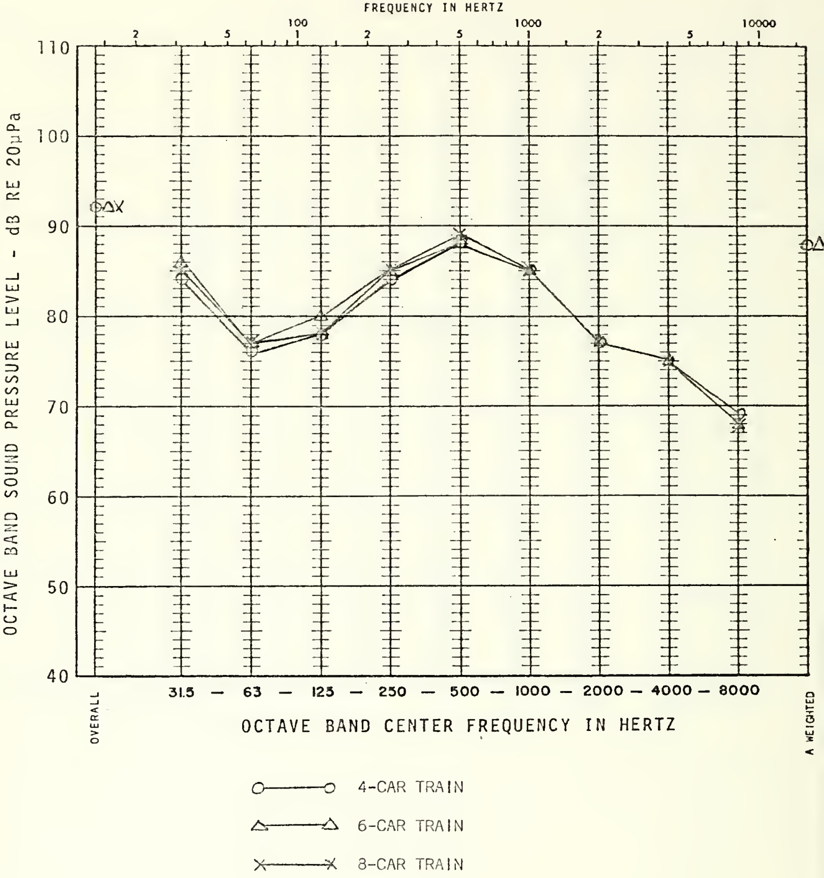


FIGURE B 30 WAYSIDE NOISE LEVEL FOR LONG 2000 SERIES TRAINS

WORN CONTINUOUS WELDED RAIL - BEFORE SMOOTHING
25 FT FROM TRACK ℄ - 30 MPH

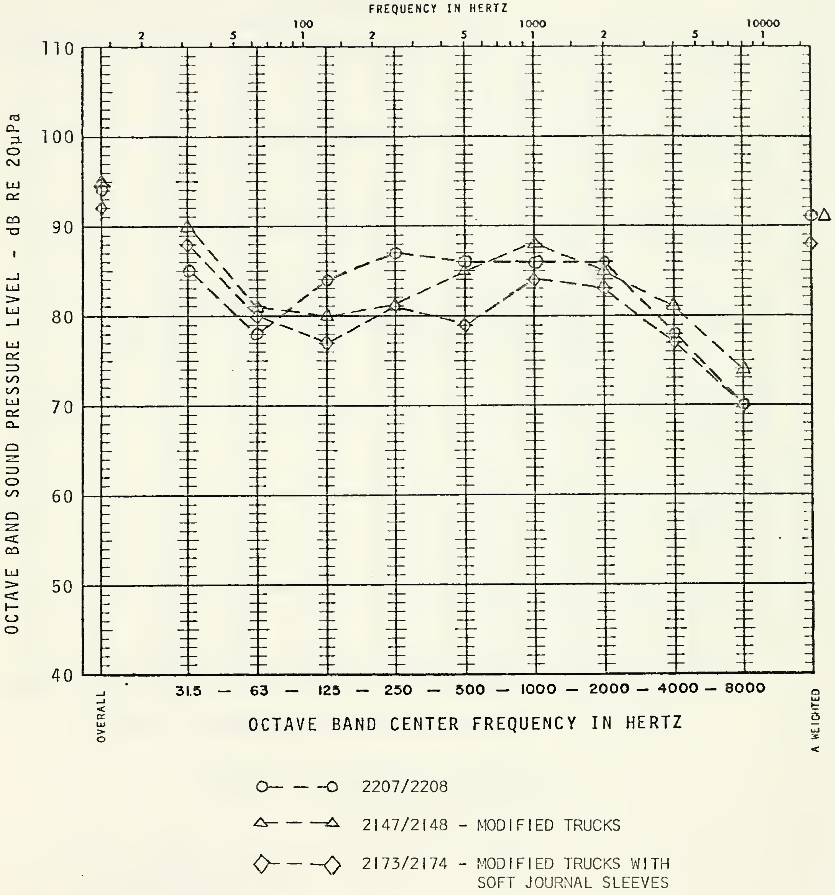


FIGURE B31 WAYSIDE NOISE LEVEL FOR 2-CAR TRAINS ON BALLAST & TIE TRACKS

NEW CONTINUOUS WELDED RAIL - BEFORE SMOOTHING

50 FT FROM TRACK ℄ - 60 MPH

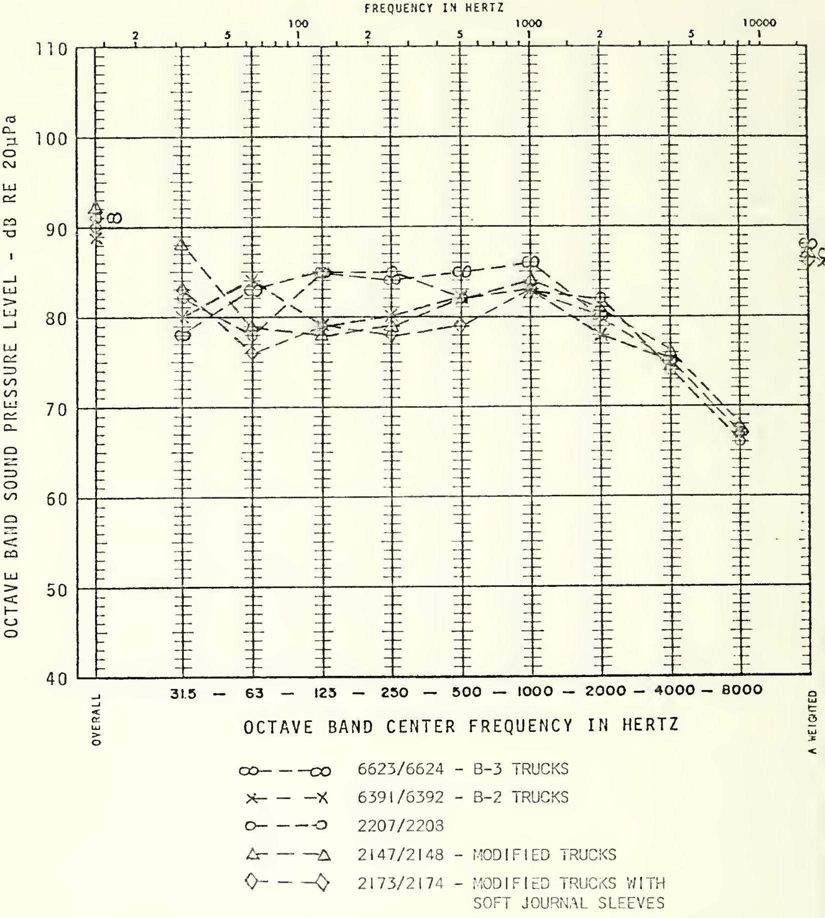


FIGURE B32 WAYSIDE NOISE LEVEL FOR 2-CAR TRAINS ON BALLAST & TIE TRACKS

NEW CONTINUOUS WELDED RAIL - BEFORE SMOOTHING

50 FT FROM TRACK ℄ - 50 MPH

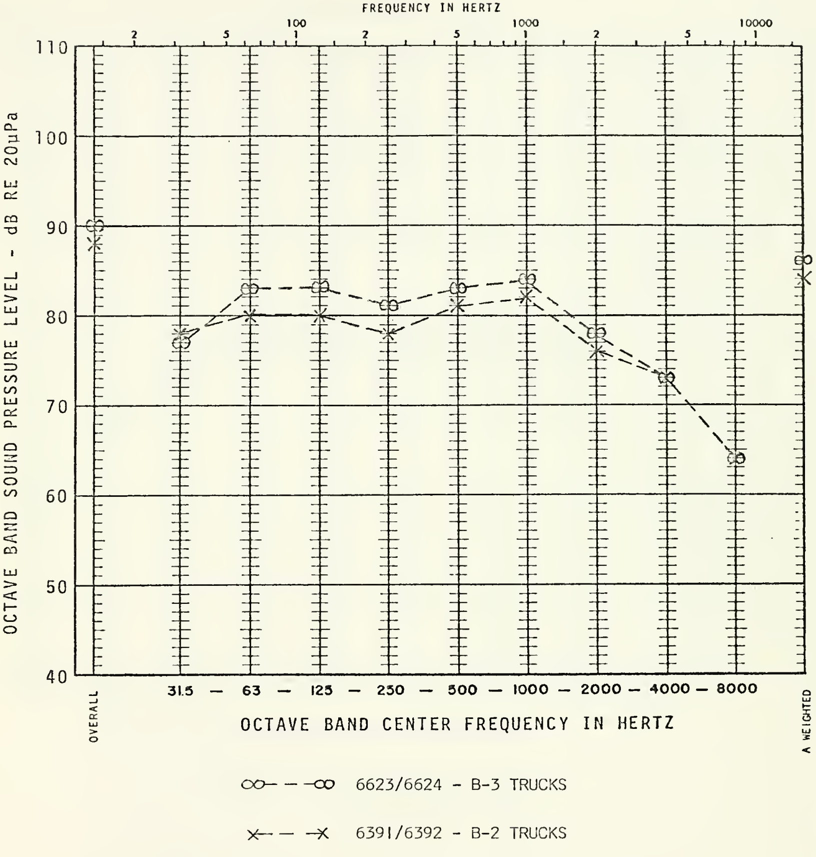
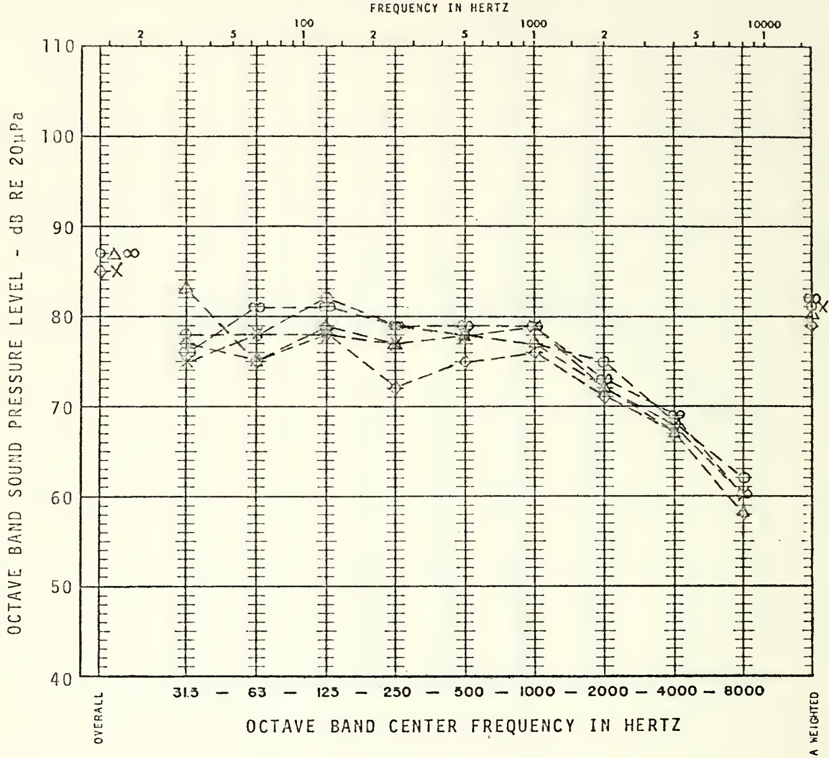


FIGURE B 33 WAYSIDE NOISE LEVEL FOR 2-CAR TRAINS ON BALLAST & TIE TRACKS

NEW CONTINUOUS WELDED RAIL - BEFORE SMOOTHING

50 FT FROM TRACK ℄ - 40 MPH



6623/6624 - B-3 TRUCKS
6391/6392 - B-2 TRUCKS
2207/2208
2147/2148 - MODIFIED TRUCKS
2173/2174 - MODIFIED TRUCKS WITH SOFT JOURNAL SLEEVES

FIGURE B34 WAYSIDE NOISE LEVEL FOR 2-CAR TRAINS ON BALLAST & TIE TRACKS

NEW CONTINUOUS WELDED RAIL - BEFORE SMOOTHING

50 FT FROM TRACK ℄ - 30 MPH

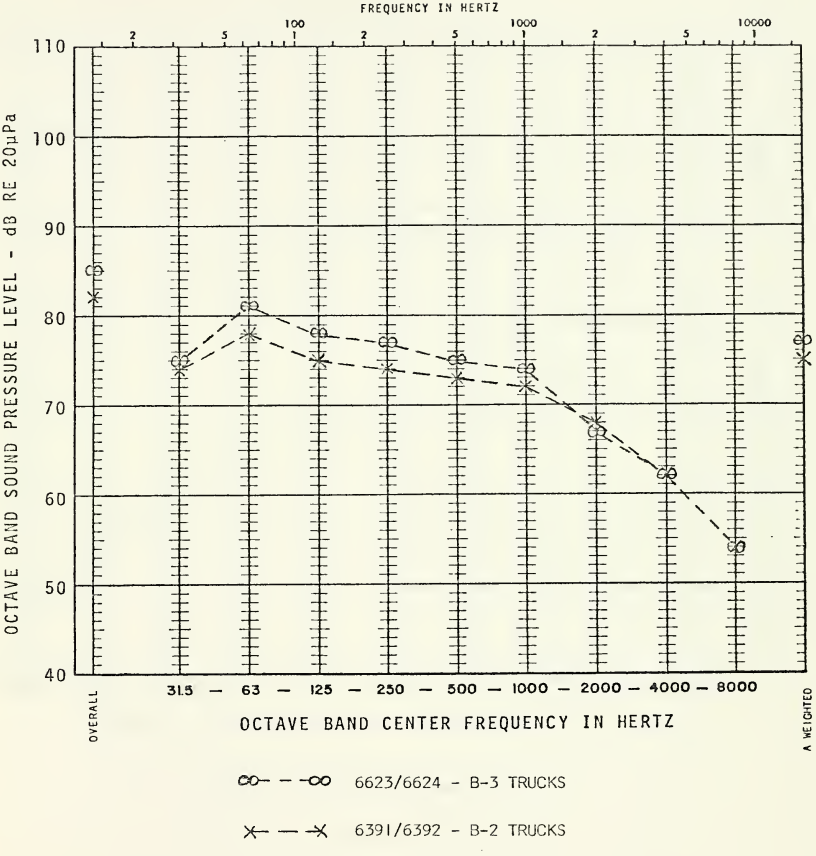


FIGURE B35 WAYSIDE NOISE LEVEL FOR 2-CAR TRAINS ON BALLAST & TIE TRACKS

NEW CONTINUOUS WELDED RAIL - BEFORE SMOOTHING

50 FT FROM TRACK ℄ - 20 MPH

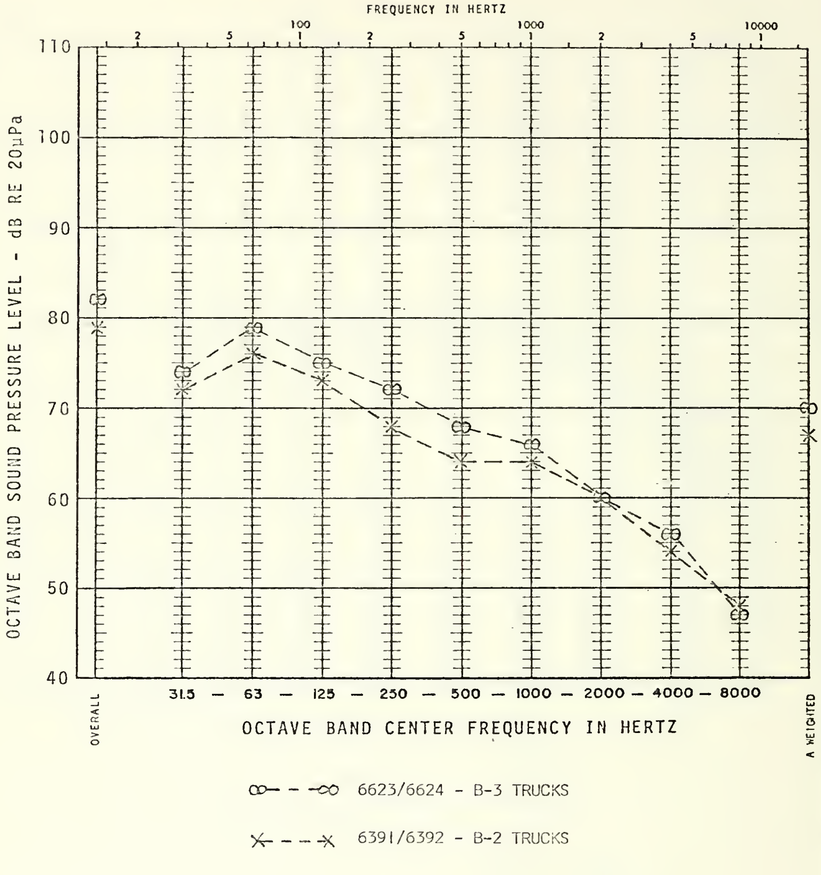


FIGURE B 36 WAYSIDE NOISE LEVEL FOR 2-CAR TRAINS ON BALLAST & TIE TRACKS

NEW CONTINUOUS WELDED RAIL - BEFORE SMOOTHING

50 FT FROM TRACK ℄ - 10 MPH

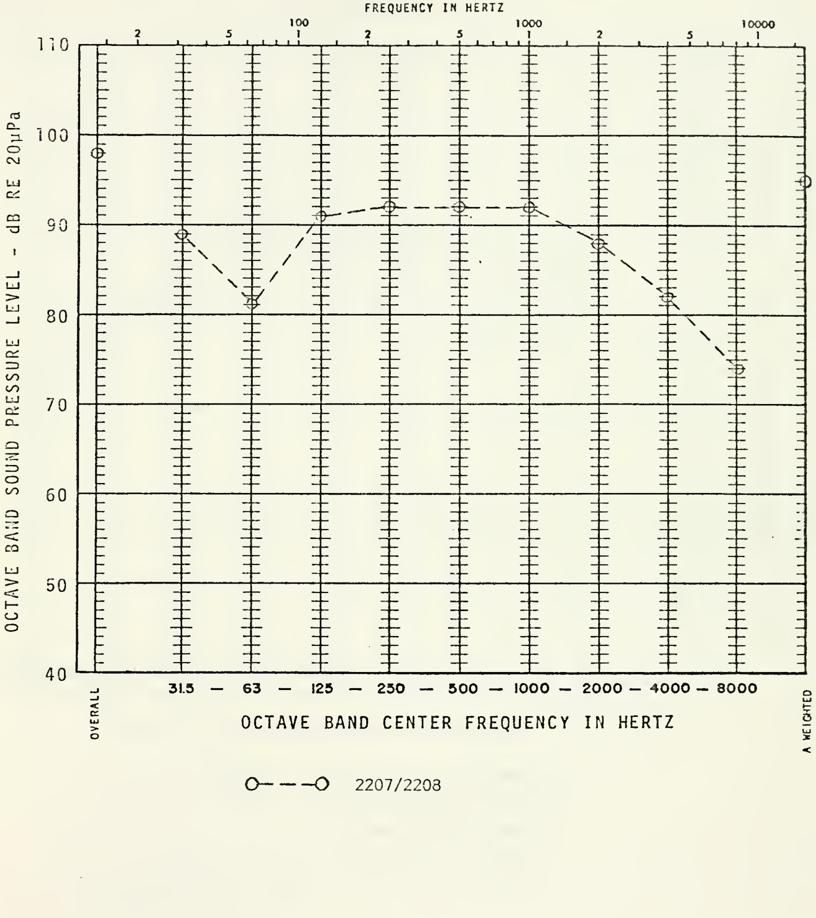


FIGURE B37 WAYSIDE NOISE LEVEL FOR 2-CAR TRAINS ON BALLAST & TIE TRACKS

NEW CONTINUOUS WELDED RAIL - BEFORE SMOOTHING

25 FT FROM TRACK - 60 MPH

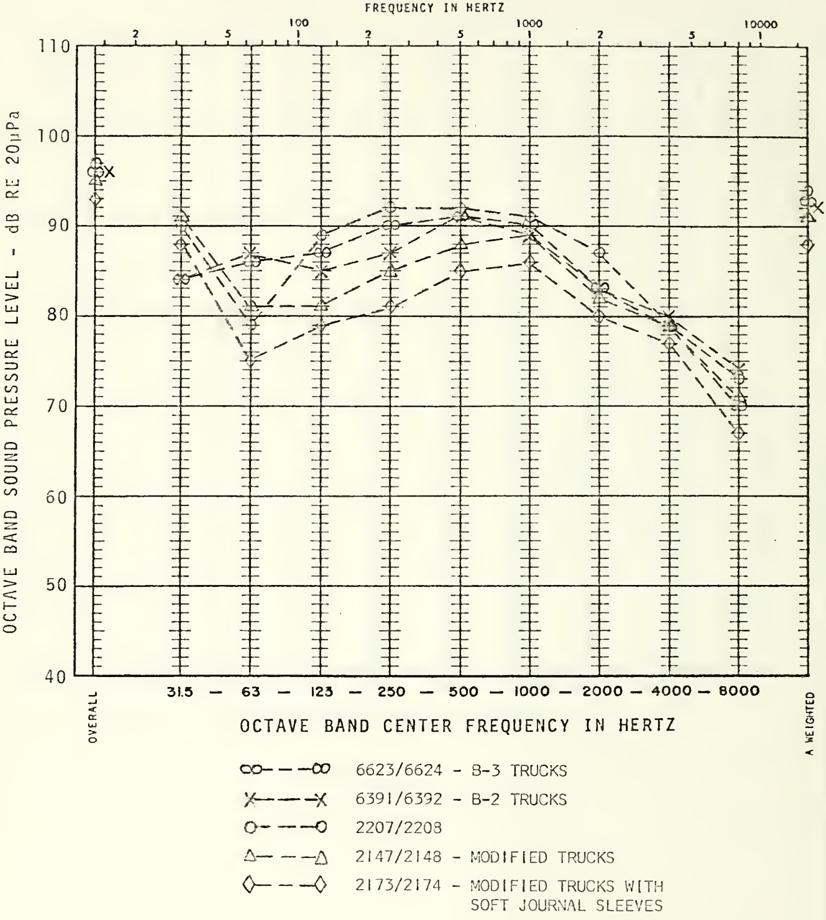


FIGURE B38 WAYSIDE NOISE LEVEL FOR 2-CAR TRAINS ON BALLAST & TIE TRACKS

NEW CONTINUOUS WELDED RAIL - BEFORE SMOOTHING

25 FT FROM TRACK ℄ - 50 MPH

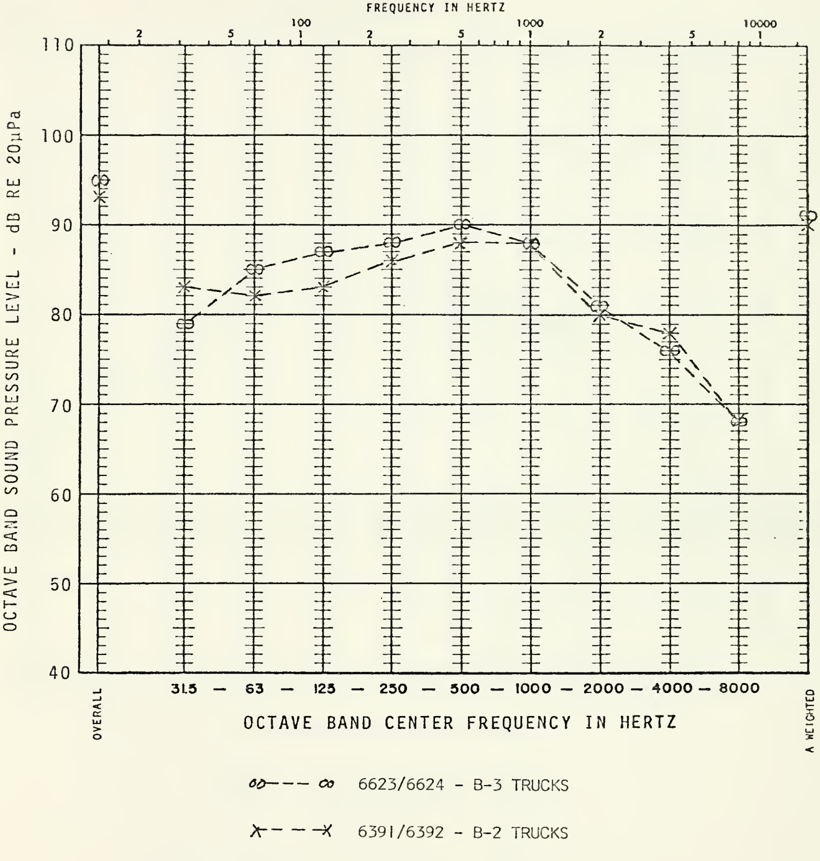


FIGURE B39 WAYSIDE NOISE LEVEL FOR 2-CAR TRAINS ON BALLAST & TIE TRACKS

NEW CONTINUOUS WELDED RAIL - BEFORE SMOOTHING

25 FT FROM TRACK ℄ - 40 MPH

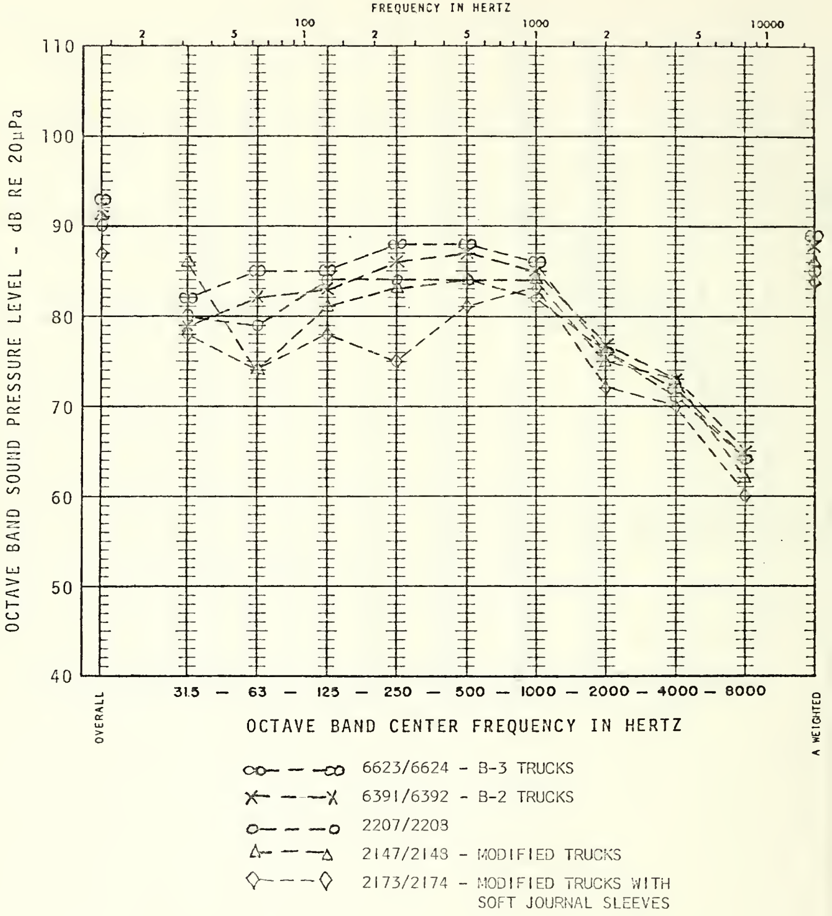


FIGURE B40 WAYSIDE NOISE LEVEL FOR 2-CAR TRAINS ON BALLAST & TIE TRACKS

NEW CONTINUOUS WELDED RAIL - BEFORE SMOOTHING

25 FT FROM TRACK ℄ - 30 MPH

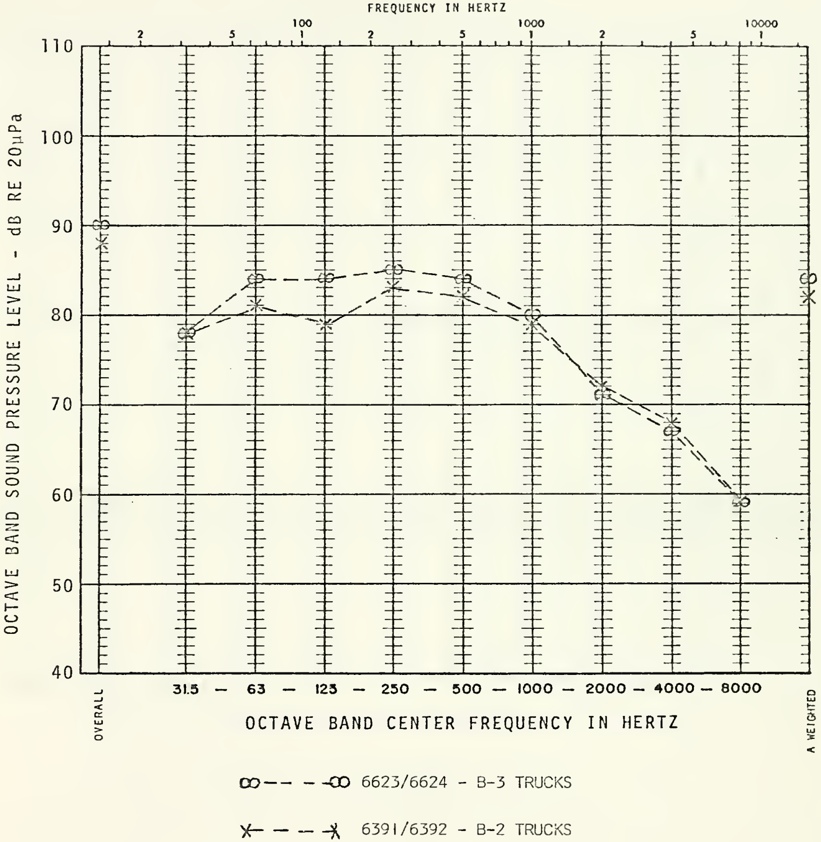


FIGURE B41 WAYSIDE NOISE LEVEL FOR 2-CAR TRAINS ON BALLAST & TIE TRACKS

NEW CONTINUOUS WELDED RAIL - BEFORE SMOOTHING

25 FT FROM TRACK ℄ - 20 MPH

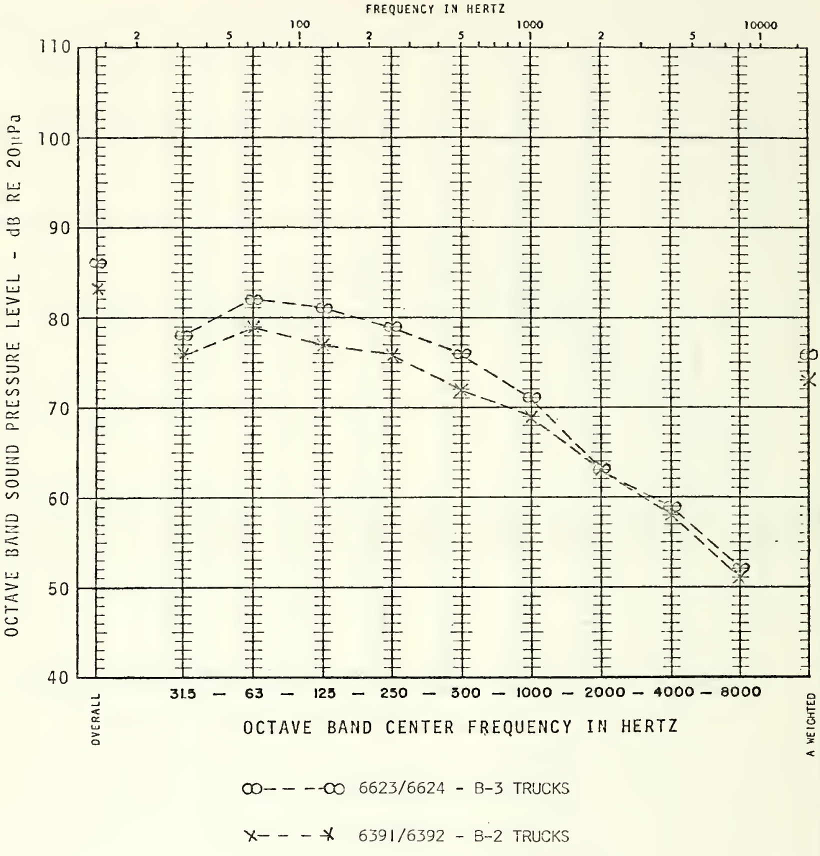


FIGURE B42 WAYSIDE NOISE LEVEL FOR 2-CAR TRAINS ON BALLAST & TIE TRACKS

NEW CONTINUOUS WELDED RAIL - BEFORE SMOOTHING

25 FT FROM TRACK ℄ - 10 MPH

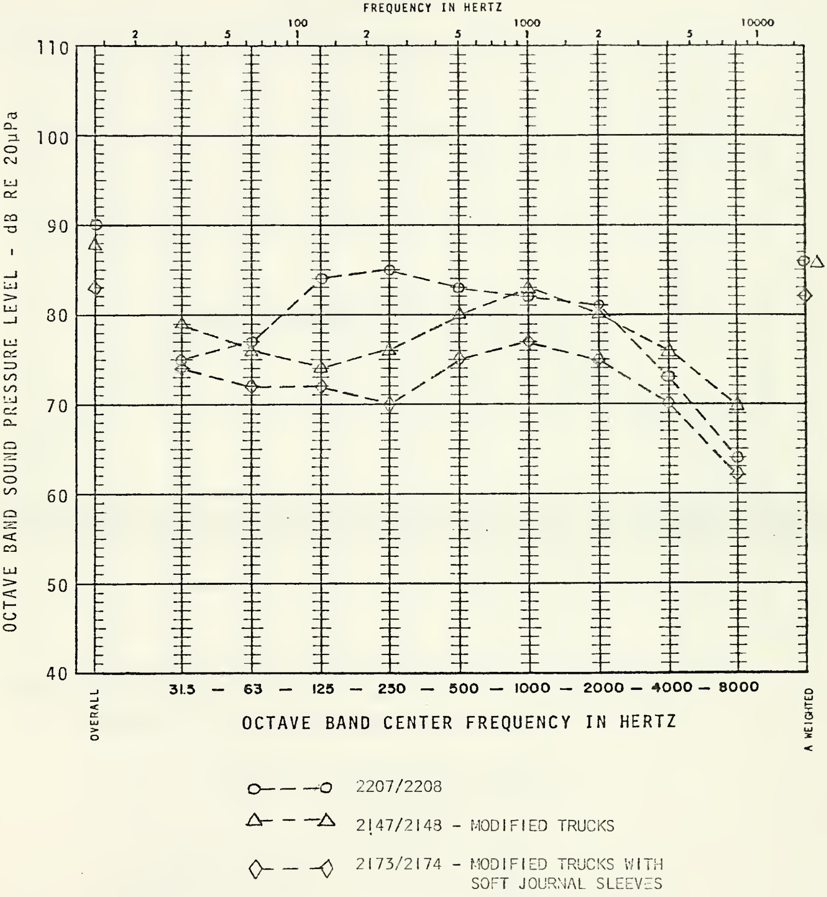


FIGURE B43 WAYSIDE NOISE LEVEL FOR 2-CAR TRAINS ON BALLAST & TIE TRACKS

NEW CONTINUOUS WELDED RAIL - AFTER SMOOTHING

50 FT FROM TRACK ℄ - 60 MPH

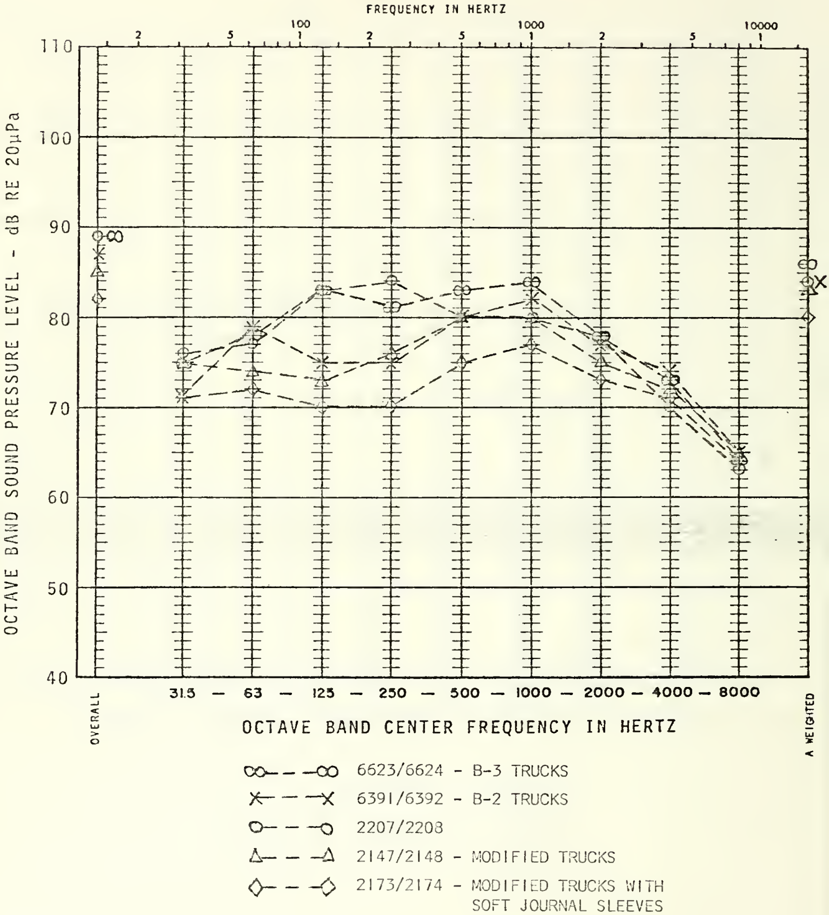


FIGURE B44 WAYSIDE NOISE LEVEL FOR 2-CAR TRAINS ON BALLAST & TIE TRACKS

NEW CONTINUOUS WELDED RAIL - AFTER SMOOTHING

50 FT FROM TRACK ℄ - 50 MPH

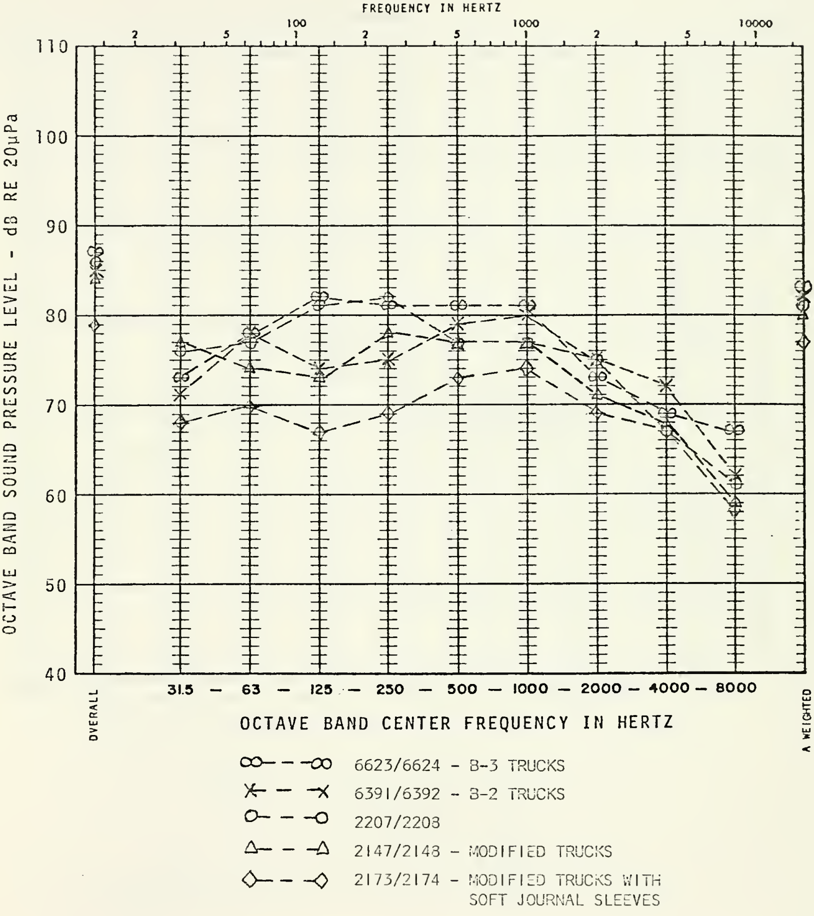


FIGURE B 45 WAYSIDE NOISE LEVEL FOR 2-CAR TRAINS ON BALLAST & TIE TRACKS

NEW CONTINUOUS WELDED RAIL - AFTER SMOOTHING

50 FT FROM TRACK ℄ - 40 MPH

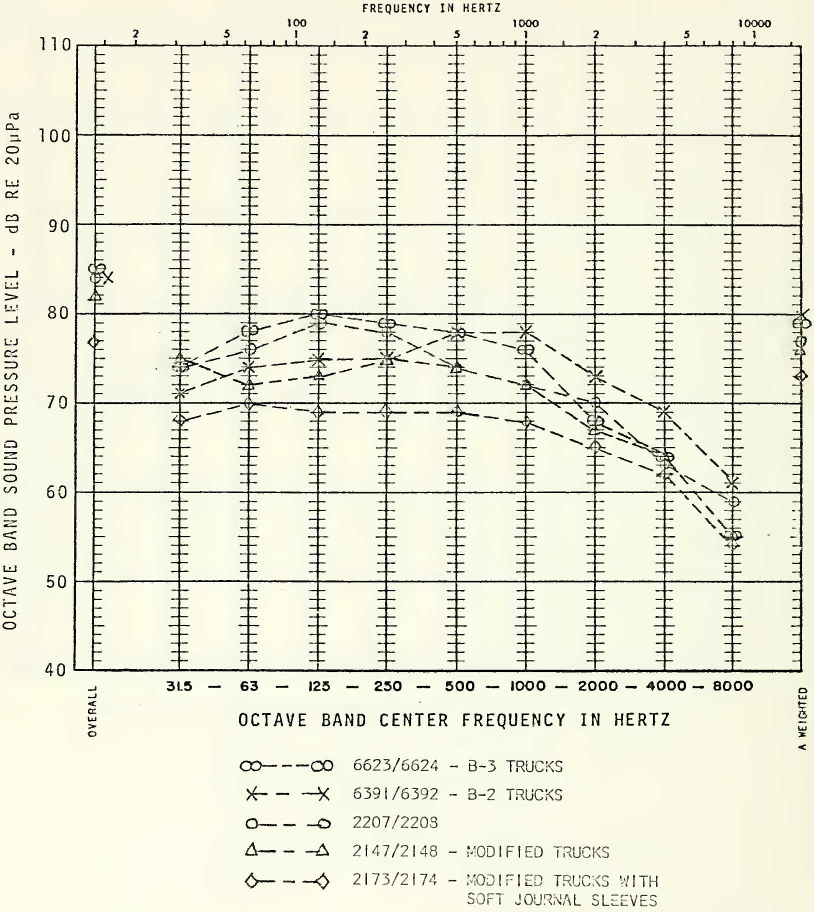


FIGURE B46 WAYSIDE NOISE LEVEL FOR 2-CAR TRAINS ON BALLAST & TIE TRACKS

NEW CONTINUOUS WELDED RAIL - AFTER SMOOTHING

50 FT FROM TRACK ℄ - 30 MPH

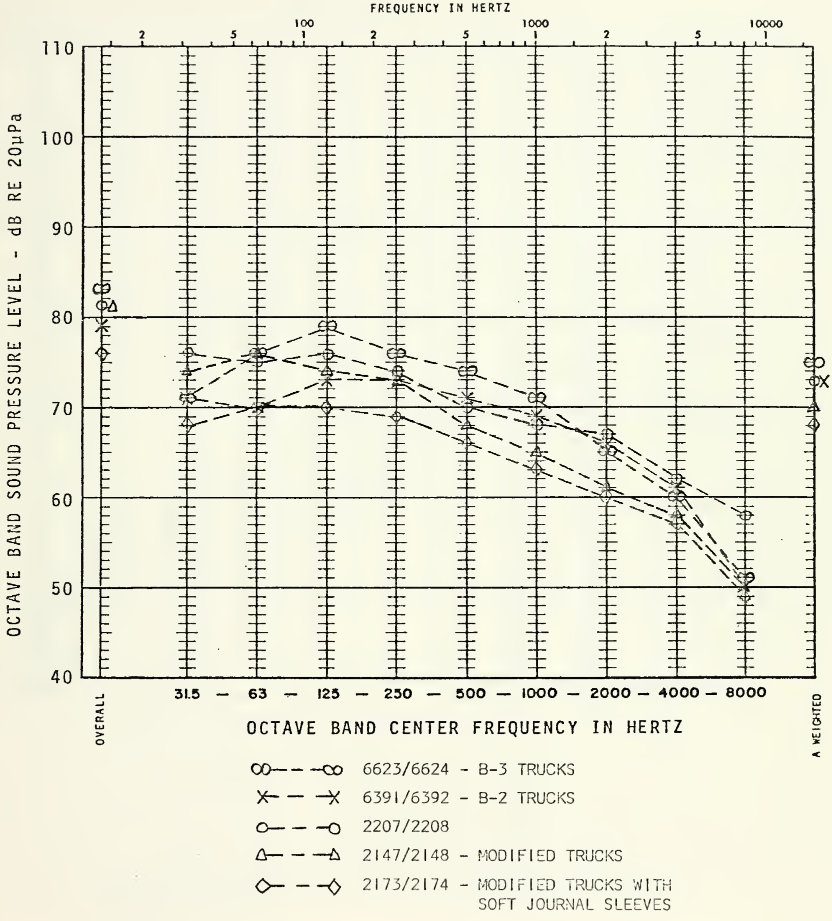


FIGURE B 47 WAYSIDE NOISE LEVEL FOR 2-CAR TRAINS ON BALLAST & TIE TRACKS

NEW CONTINUOUS WELDED RAIL - AFTER SMOOTHING

50 FT FROM TRACK ℄ - 20 MPH

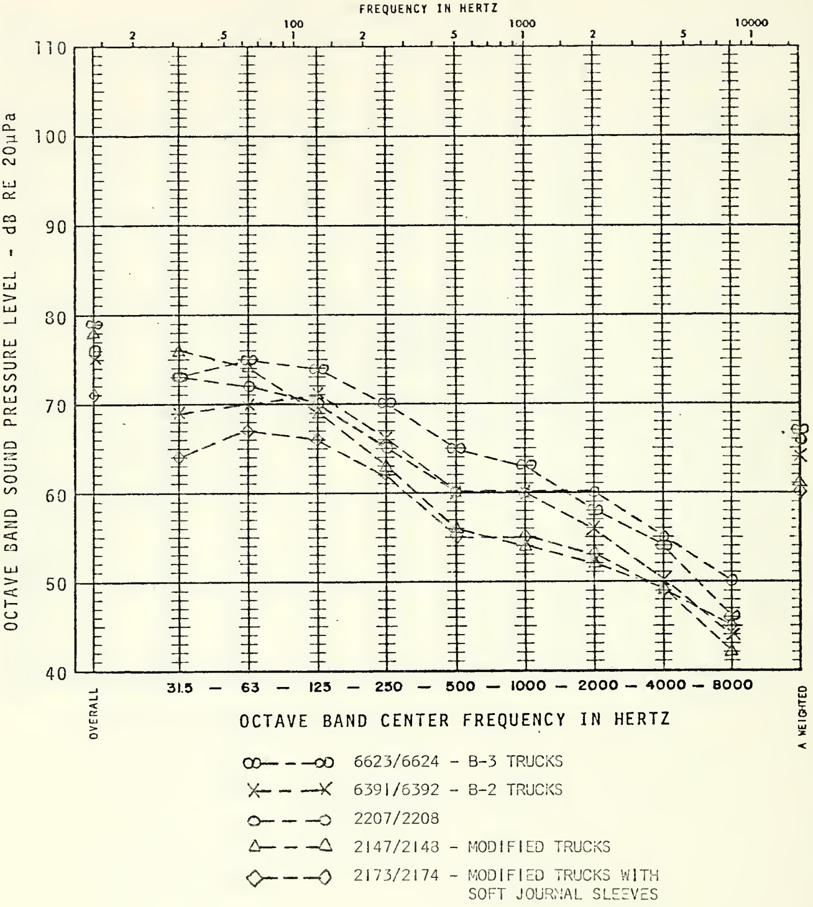
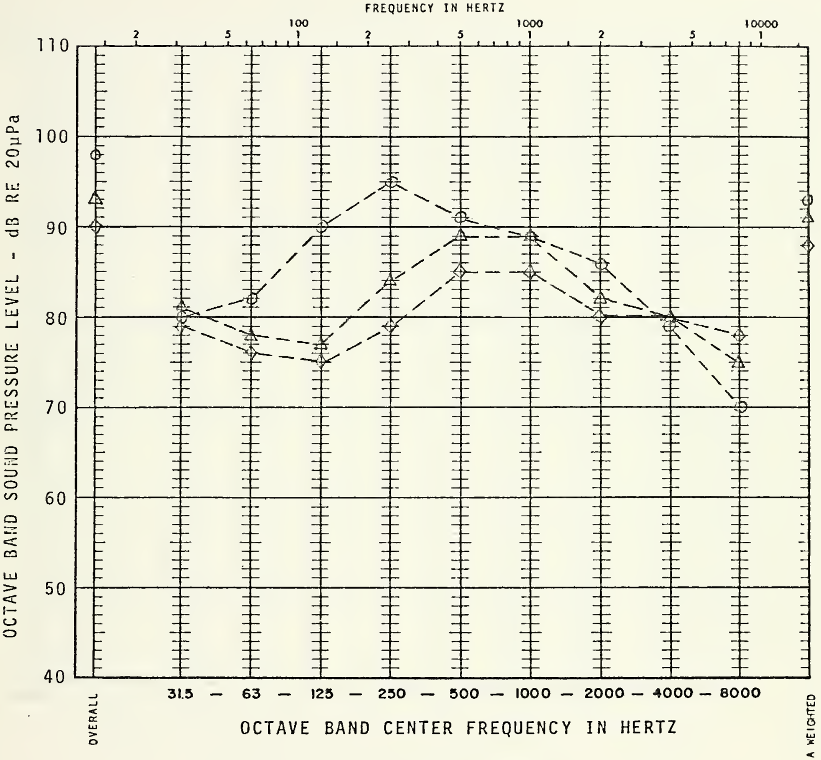


FIGURE B48 WAYSIDE NOISE LEVEL FOR 2-CAR TRAINS ON BALLAST & TIE TRACKS

NEW CONTINUOUS WELDED RAIL - AFTER SMOOTHING

50 FT FROM TRACK ℄ - 10 MPH



○- - -○ 2207/2208

△- - -△ 2147/2148 - MODIFIED TRUCKS

◇- - -◇ 2173/2174 - MODIFIED TRUCKS WITH SOFT JOURNAL SLEEVES

FIGURE B49 WAYSIDE NOISE LEVEL FOR 2-CAR TRAINS ON BALLAST & TIE TRACKS

NEW CONTINUOUS WELDED RAIL - AFTER SMOOTHING

25 FT FROM TRACK ℄ - 60 MPH

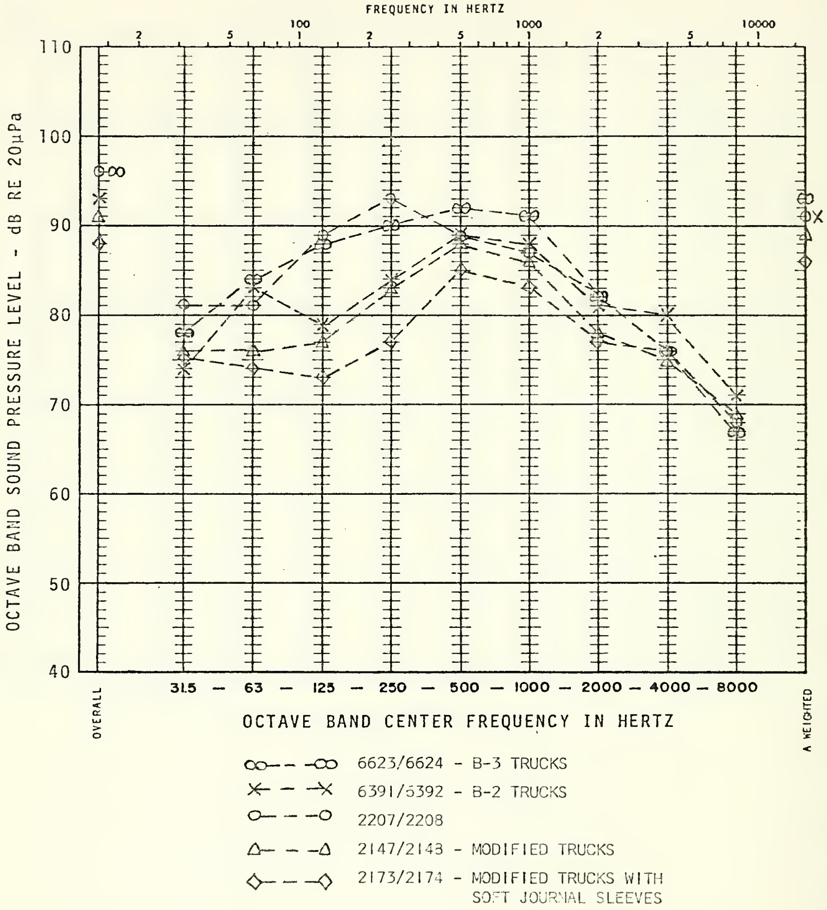


FIGURE B50 WAYSIDE NOISE LEVEL FOR 2-CAR TRAINS ON BALLAST & TIE TRACKS

NEW CONTINUOUS WELDED RAIL - AFTER SMOOTHING

25 FT FROM TRACK ℄ - 50 MPH

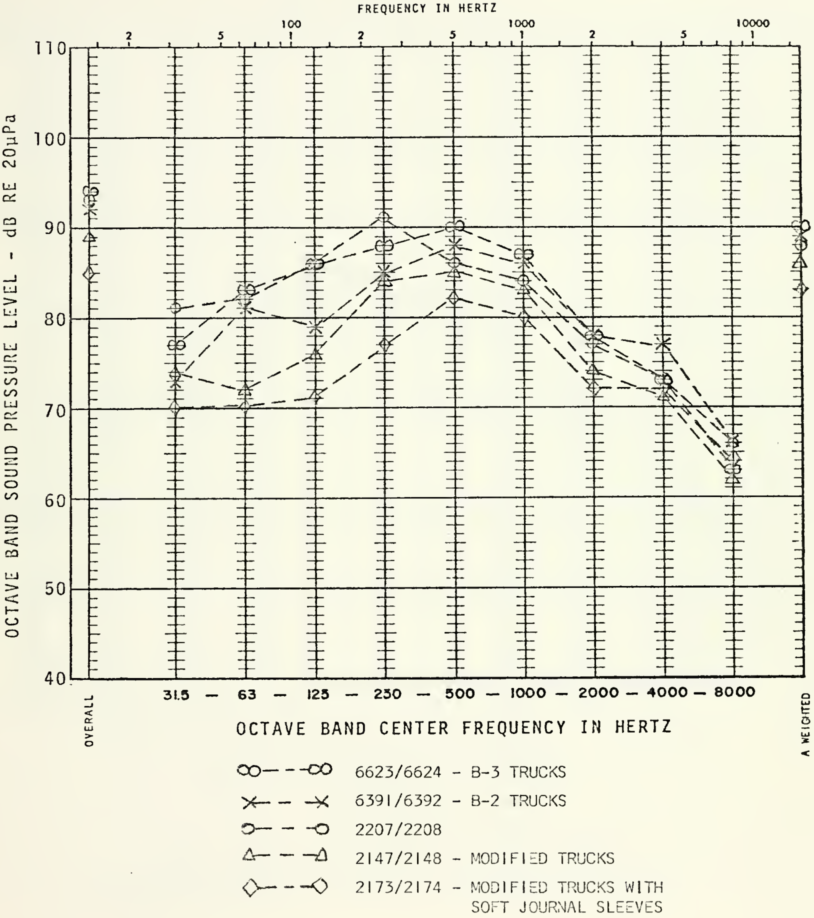


FIGURE B 51 WAYSIDE NOISE LEVEL FOR 2-CAR TRAINS ON BALLAST & TIE TRACKS

NEW CONTINUOUS WELDED RAIL - AFTER SMOOTHING

25 FT FROM TRACK ℄ - 40 MPH

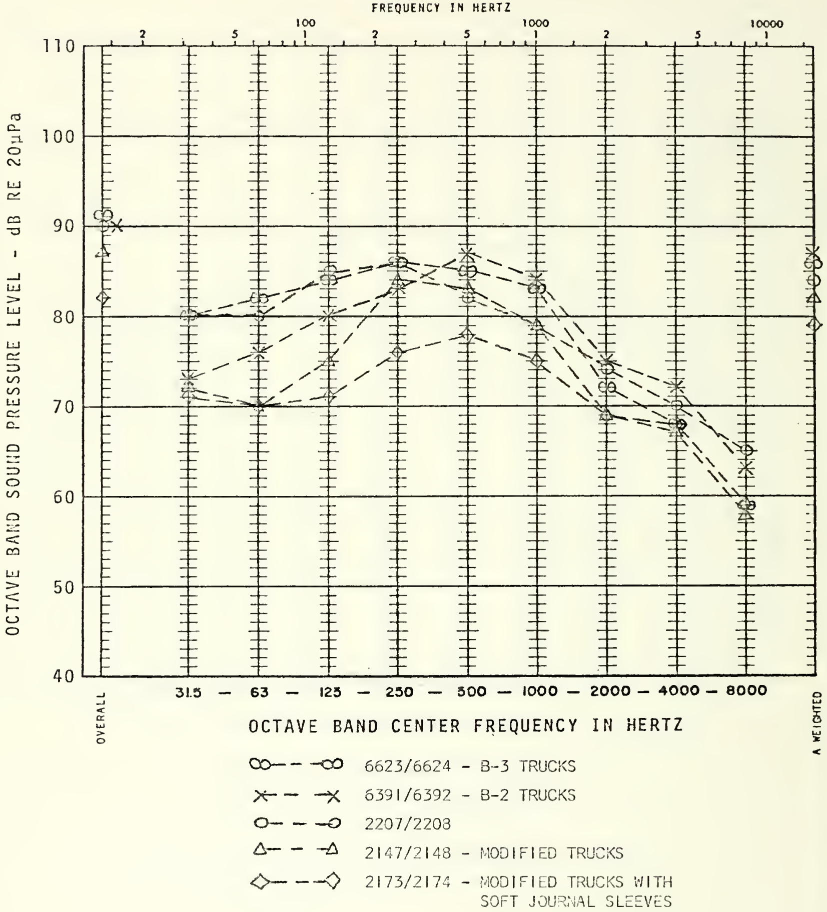


FIGURE B52 WAYSIDE NOISE LEVEL FOR 2-CAR TRAINS ON BALLAST & TIE TRACKS

NEW CONTINUOUS WELDED RAIL - AFTER SMOOTHING

25 FT FROM TRACK ℄ - 30 MPH

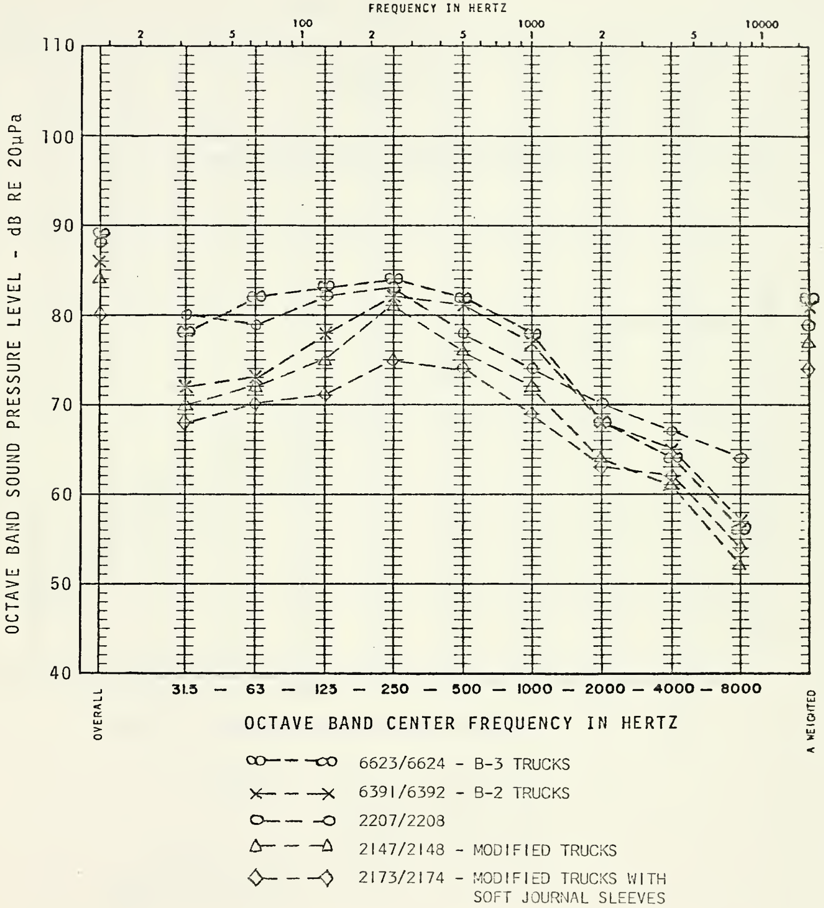


FIGURE B53 WAYSIDE NOISE LEVEL FOR 2-CAR TRAINS ON BALLAST & TIE TRACKS

NEW CONTINUOUS WELDED RAIL - AFTER SMOOTHING

25 FT FROM TRACK ℄ - 20 MPH

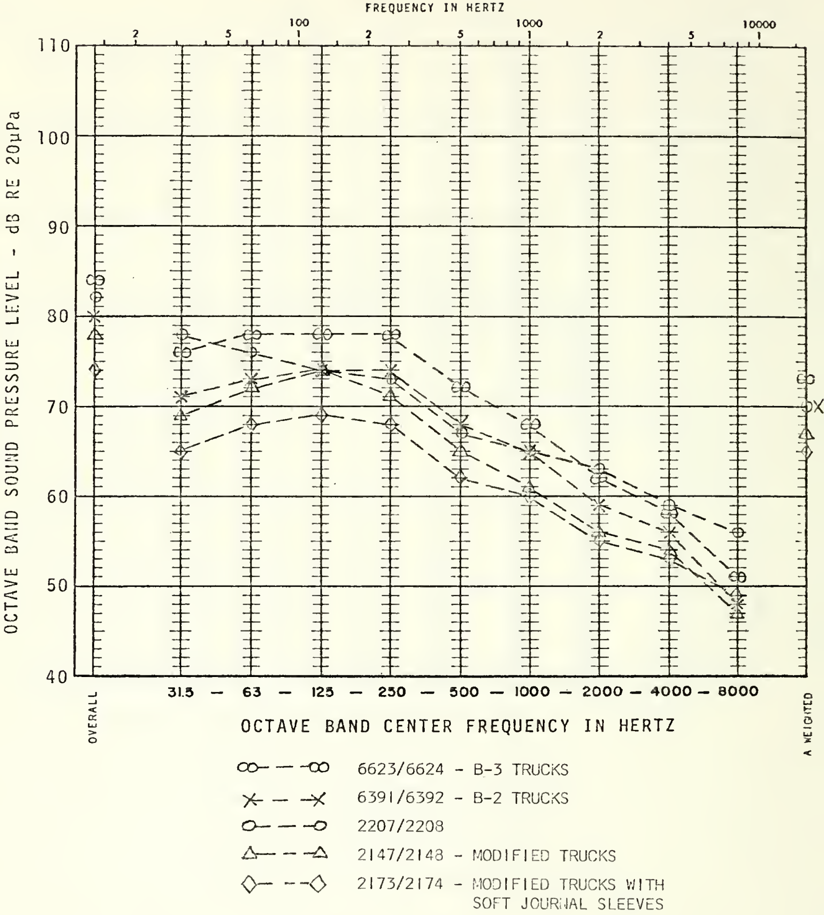


FIGURE B54 WAYSIDE NOISE LEVEL FOR 2-CAR TRAINS ON BALLAST & TIE TRACKS

NEW CONTINUOUS WELDED RAIL - AFTER SMOOTHING

25 FT FROM TRACK ℄ - 10 MPH

APPENDIX C

WAYSIDE NOISE LEVELS IN SUBWAYS

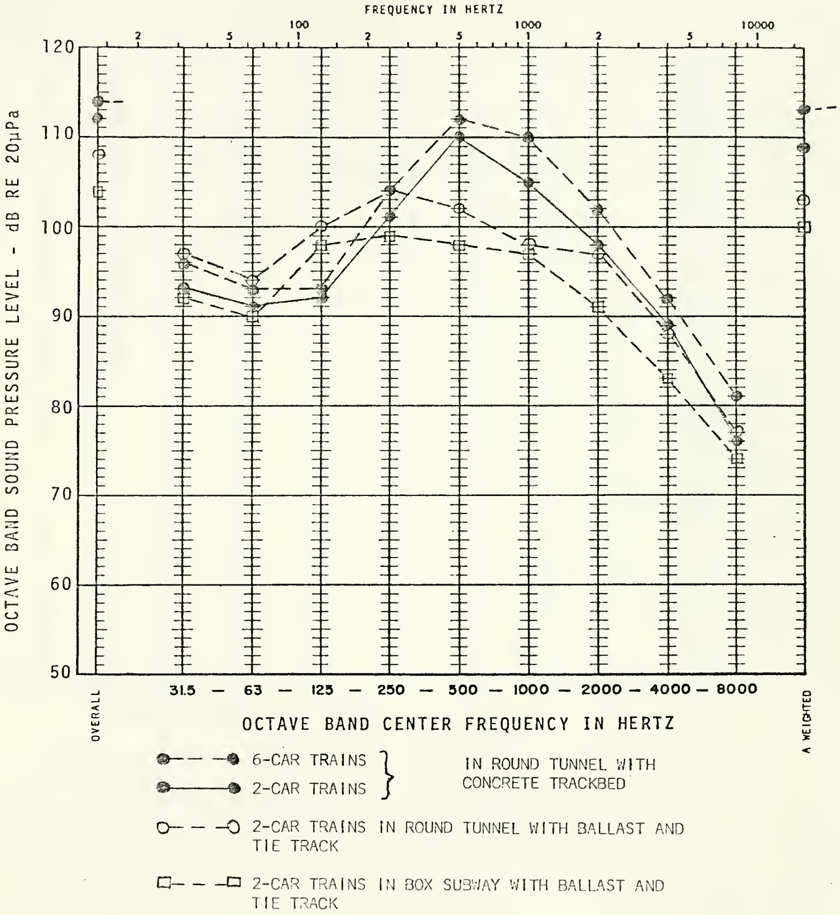


FIGURE C1 AVERAGE WAYSIDE NOISE LEVELS IN SUBWAYS WITH 2200 SERIES TRAINS PASSING BY AT 30-40 MPH

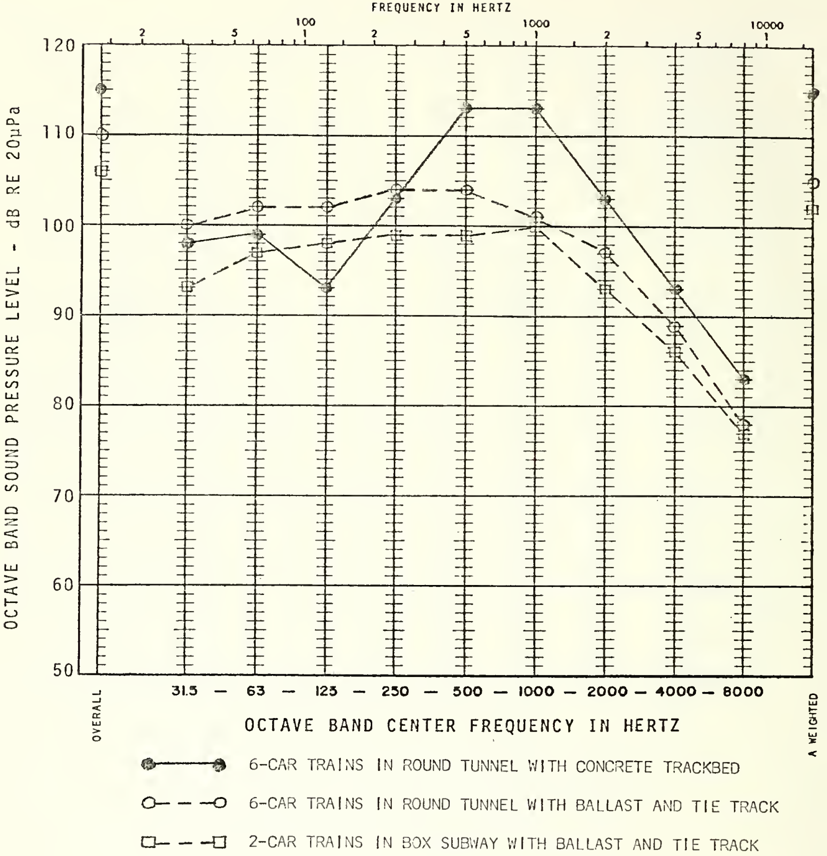


FIGURE C2 AVERAGE WAYSIDE NOISE LEVELS IN SUBWAYS WITH 6000 SERIES TRAINS PASSING BY AT 30-40 MPH

APPENDIX D

NOISE LEVELS ON SUBWAY STATION PLATFORMS

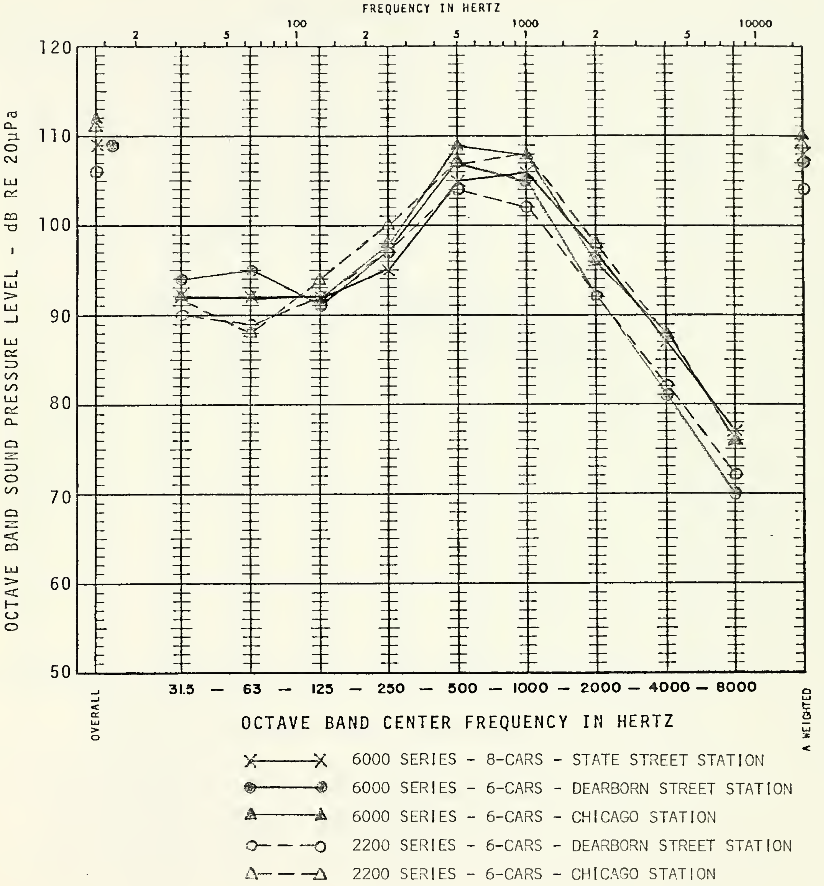


FIGURE D1 AVERAGE PLATFORM NOISE LEVELS IN SUBWAY STATIONS WITH CONCRETE TRACKBED - TRAINS PASSING THROUGH ON NEAR TRACK

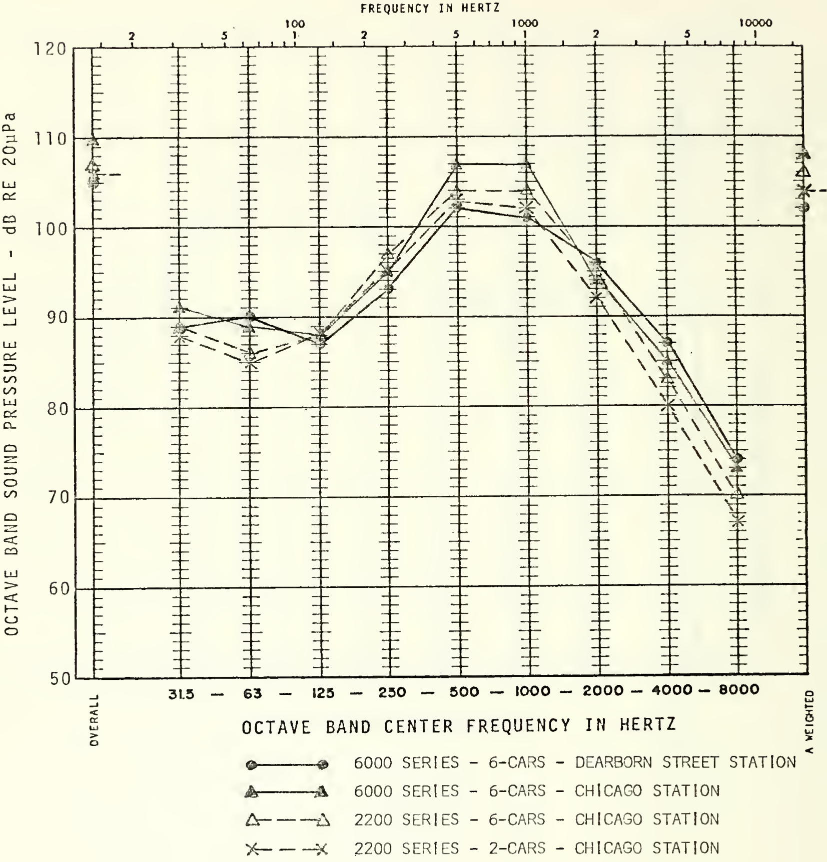


FIGURE D2 AVERAGE PLATFORM NOISE LEVELS IN SUBWAY STATIONS WITH CONCRETE TRACKBED - TRAINS PASSING THROUGH ON FAR TRACK

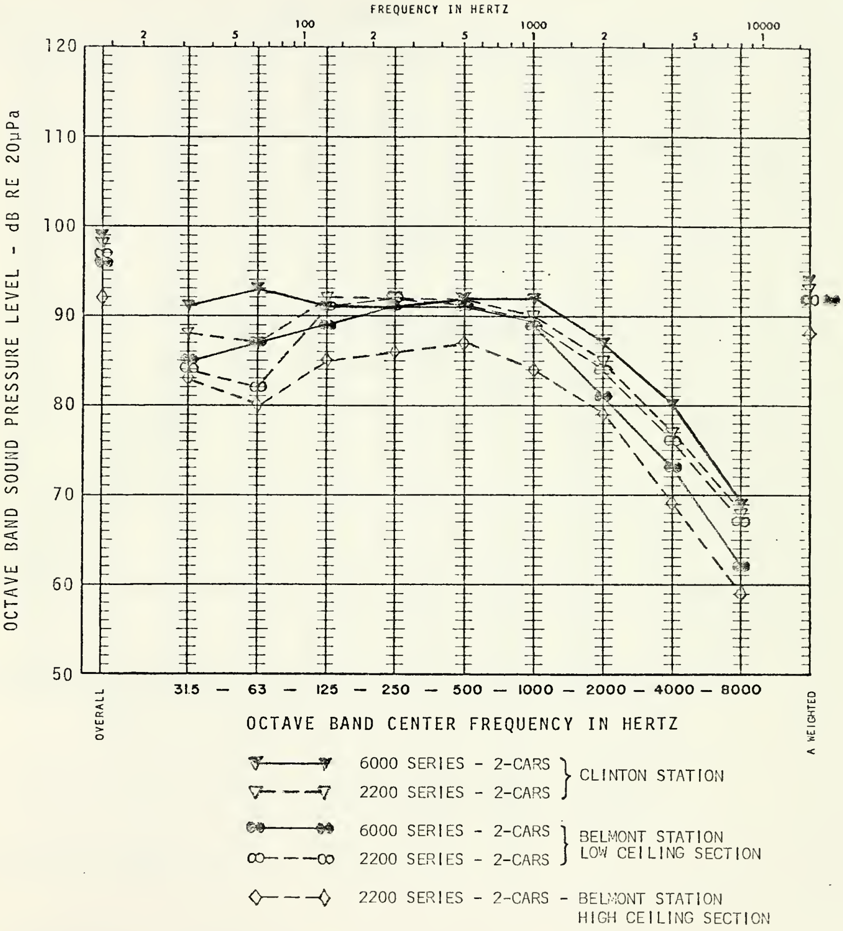


FIGURE D3 AVERAGE PLATFORM NOISE LEVELS IN SUBWAY STATIONS WITH BALLAST & TIE TRACK - TRAINS PASSING THROUGH ON NEAR TRACK

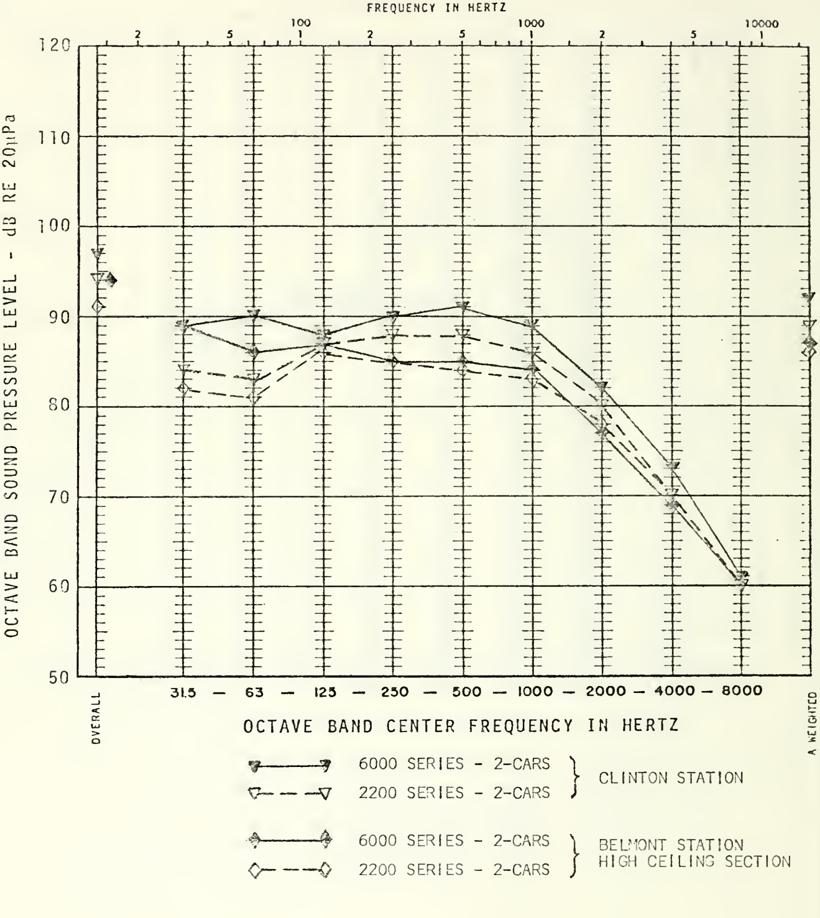


FIGURE D4 AVERAGE PLATFORM NOISE LEVELS IN SUBWAY STATIONS WITH BALLAST & TIE TRACK - TRAINS PASSING THROUGH ON FAR TRACK

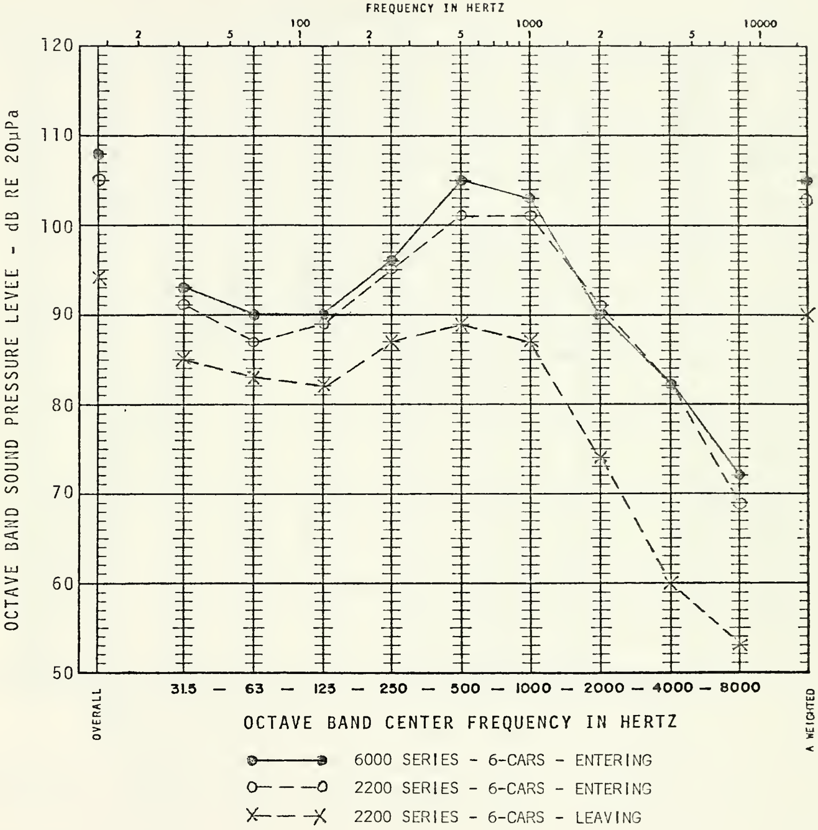


FIGURE D5 AVERAGE PLATFORM NOISE LEVELS IN SUBWAY STATIONS WITH CONCRETE TRACKBED WITH TRAINS ENTERING AND LEAVING ON NEAR TRACK - CHICAGO STATION

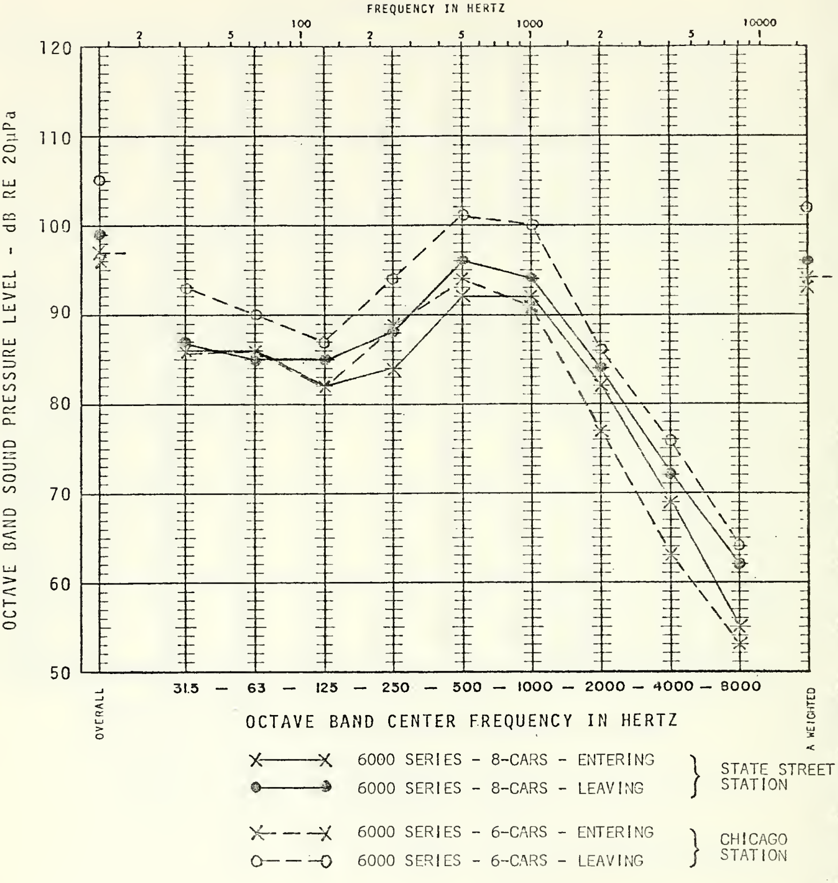


FIGURE D6 AVERAGE PLATFORM NOISE LEVELS IN SUBWAY STATIONS WITH CONCRETE TRACKBED WITH TRAINS ENTERING AND LEAVING ON FAR TRACK

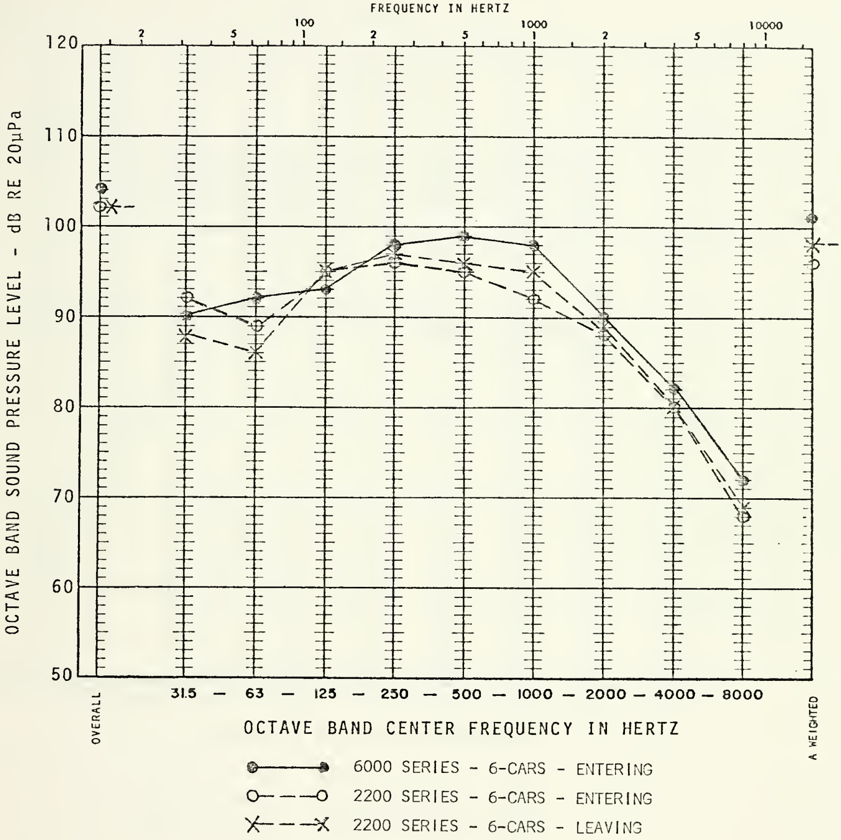


FIGURE D7 AVERAGE PLATFORM NOISE LEVELS IN SUBWAY STATIONS WITH BALLAST & TIE TRACK WITH TRAINS ENTERING AND LEAVING ON NEAR TRACK - CLINTON STATION

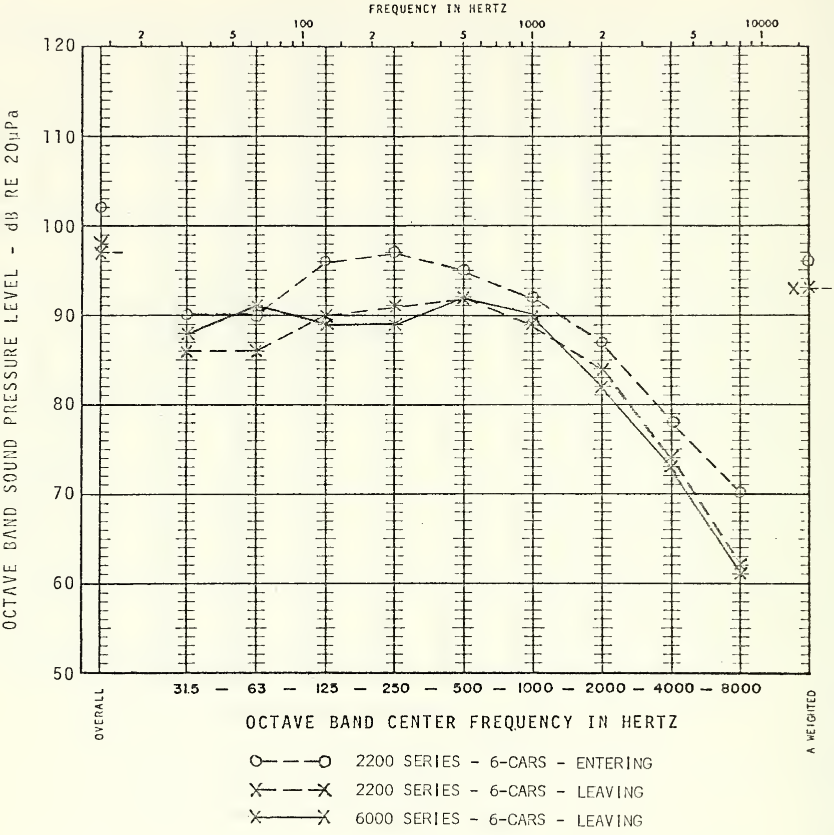


FIGURE D8 AVERAGE PLATFORM NOISE LEVELS IN SUBWAY STATIONS WITH BALLAST & TIE TRACK WITH TRAINS ENTERING AND LEAVING ON FAR TRACK - CLINTON STATION

APPENDIX E

CAR INTERIOR NOISE LEVELS FOR OPERATIONS ON ELEVATED STRUCTURE AND BALLAST AND TIE TRACK

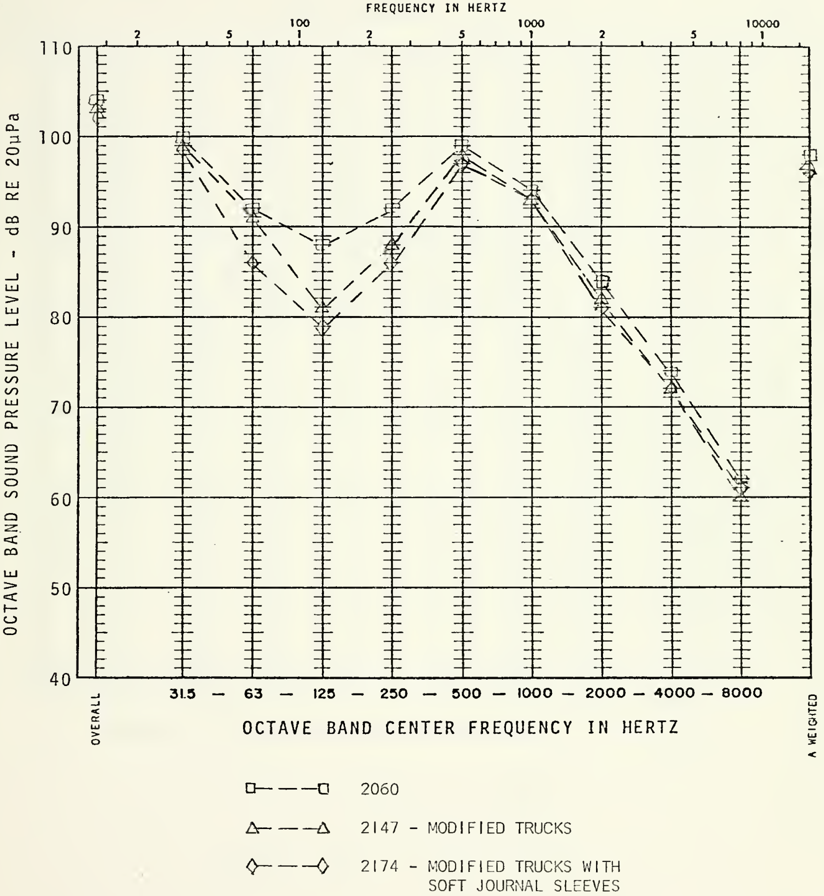


FIGURE E1 AVERAGE CAR INTERIOR NOISE LEVELS ON 2-TRACK OPEN WEB ELEVATED STRUCTURE

50 MPH

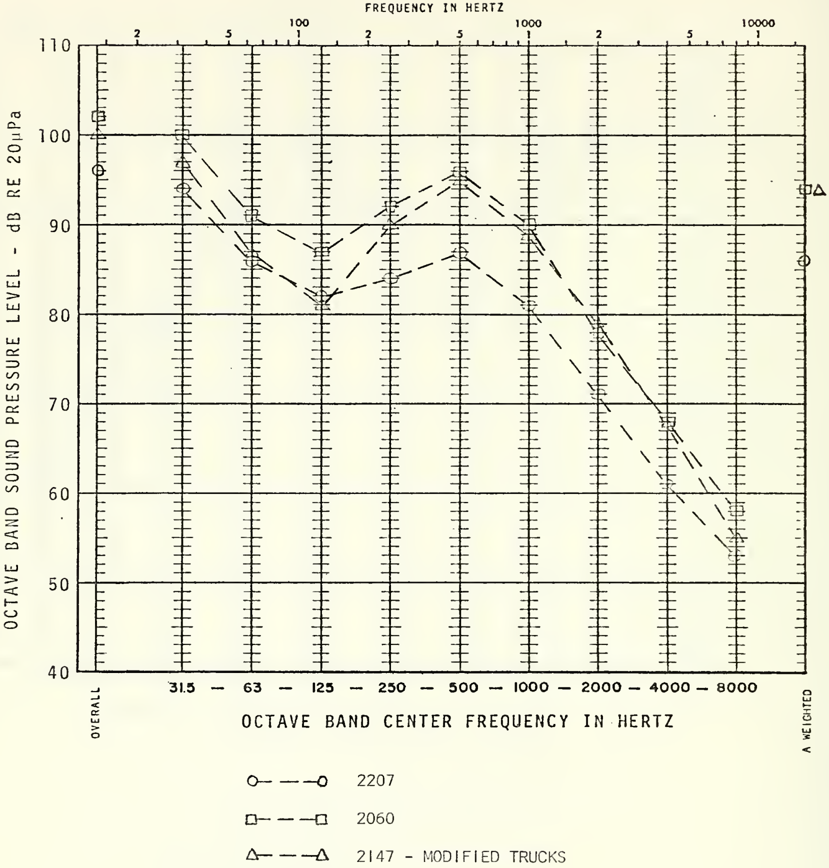


FIGURE E2 AVERAGE CAR INTERIOR NOISE LEVELS ON 2-TRACK OPEN WEB ELEVATED STRUCTURE

40 MPH

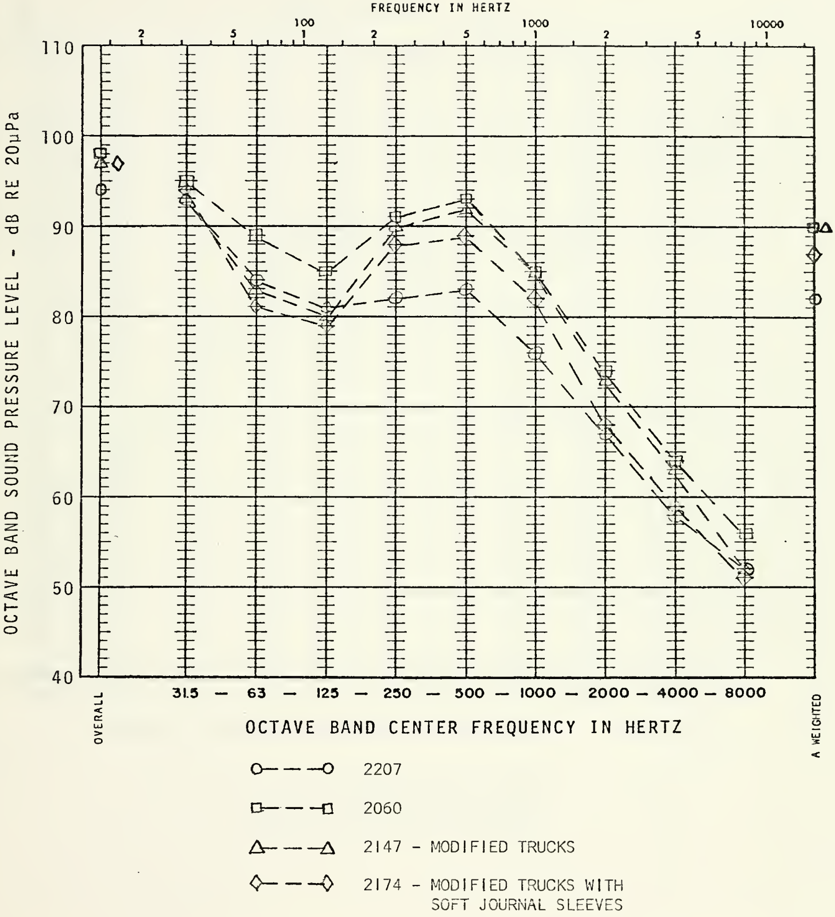


FIGURE E3 AVERAGE CAR INTERIOR NOISE LEVELS ON 2-TRACK OPEN WEB ELEVATED STRUCTURE

30 MPH

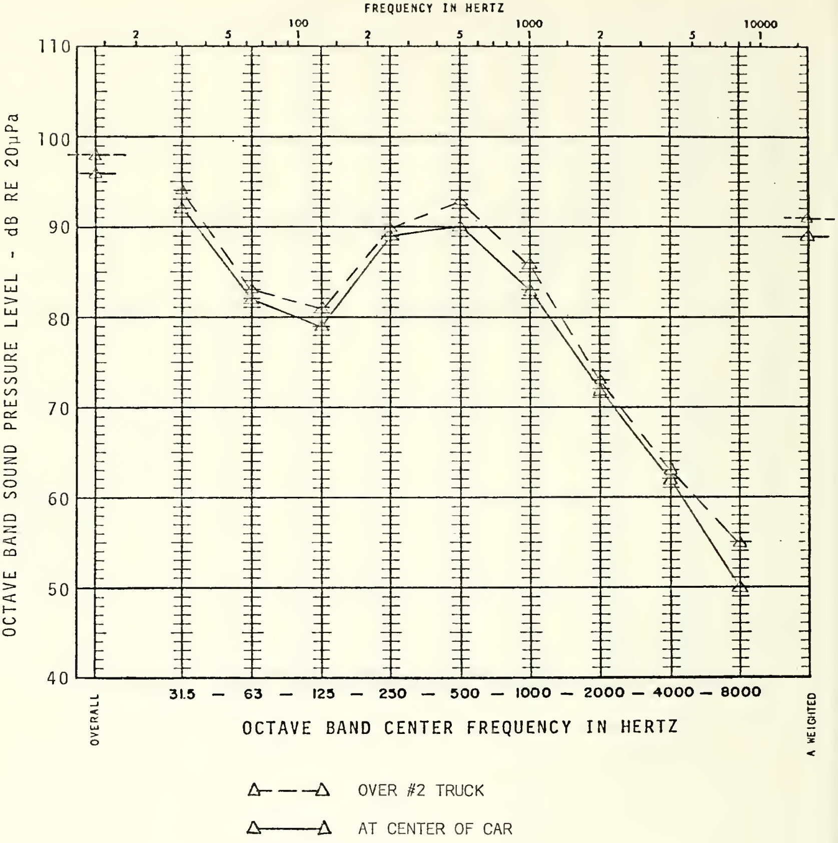


FIGURE E4 INTERIOR NOISE LEVELS FOR CAR 2147 ON 2-TRACK OPEN WEB ELEVATED STRUCTURE AT 30 MPH

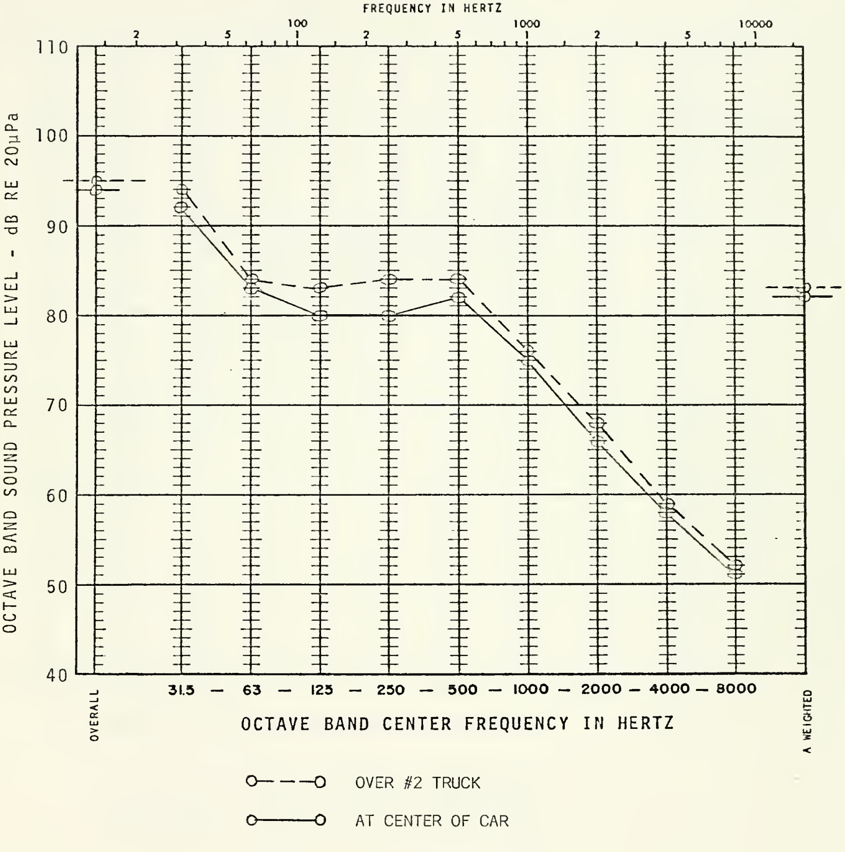


FIGURE E5 INTERIOR NOISE LEVELS FOR CAR 2207 ON 2-TRACK OPEN WEB ELEVATED STRUCTURE AT 30 MPH

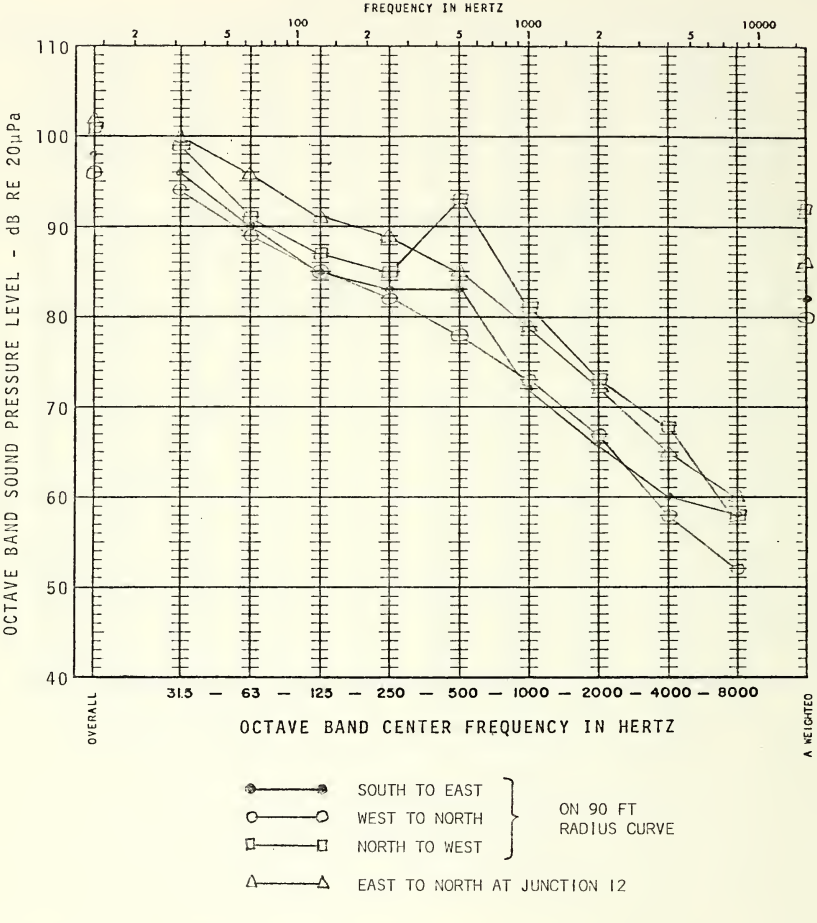


FIGURE E6 INTERIOR NOISE LEVELS FOR CAR 2207 OPERATING ON THE LOOP ELEVATED AT 10 MPH

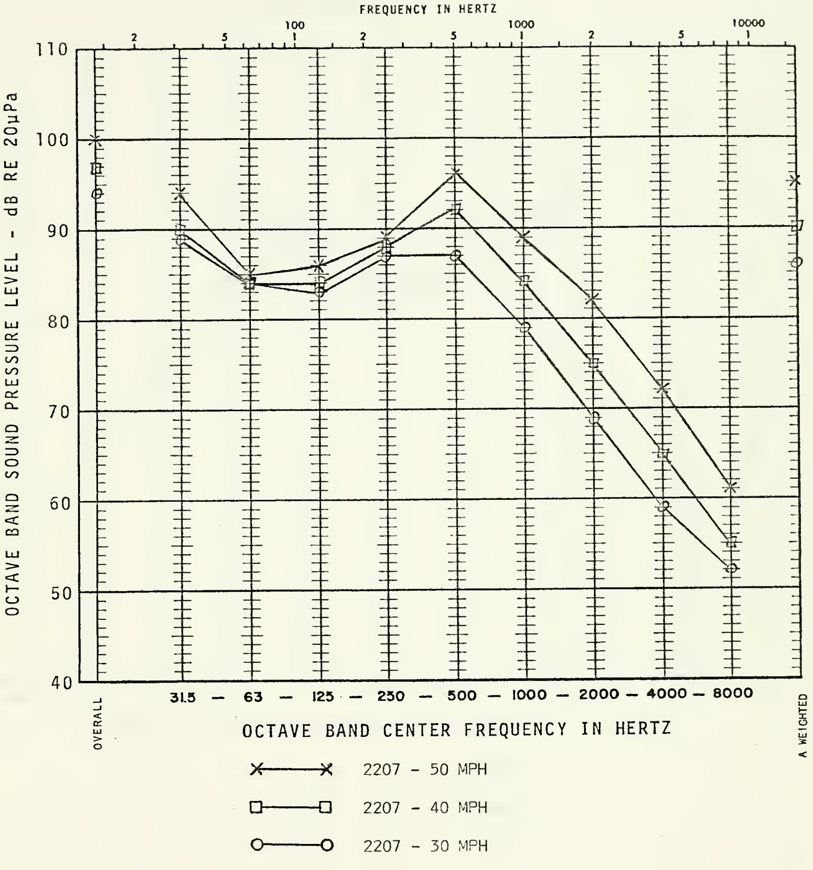


FIGURE E7 AVERAGE CAR INTERIOR NOISE LEVELS FOR CAR 2207 ON 2-TRACK SOLID WEB ELEVATED STRUCTURE

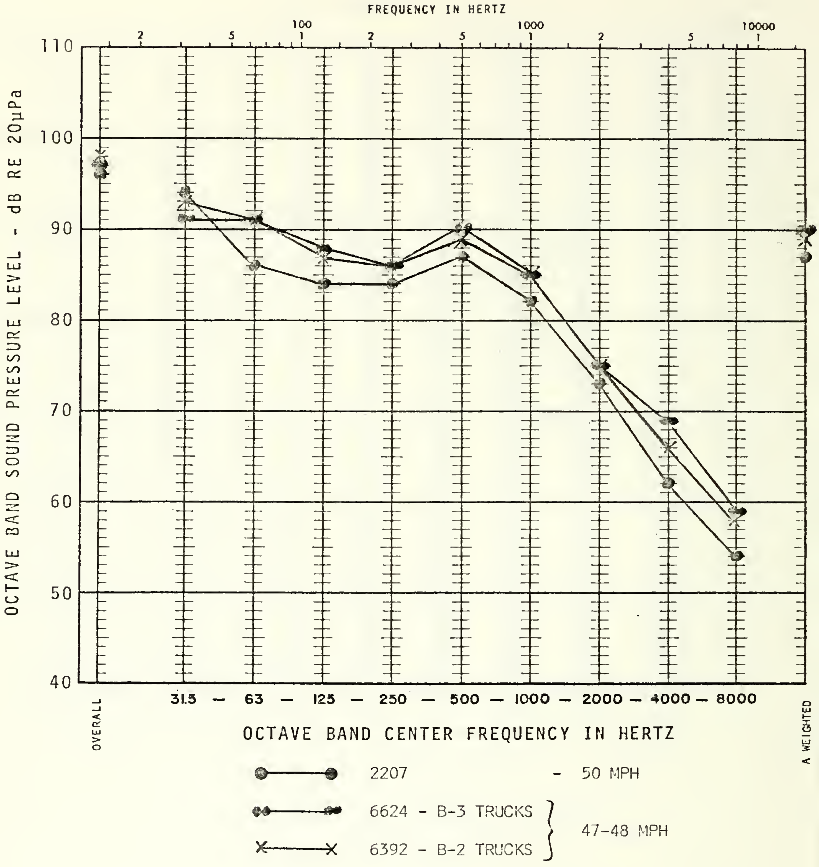


FIGURE E8 AVERAGE CAR INTERIOR NOISE LEVELS ON 4-TRACK SOLID WEB ELEVATED STRUCTURE

50 MPH

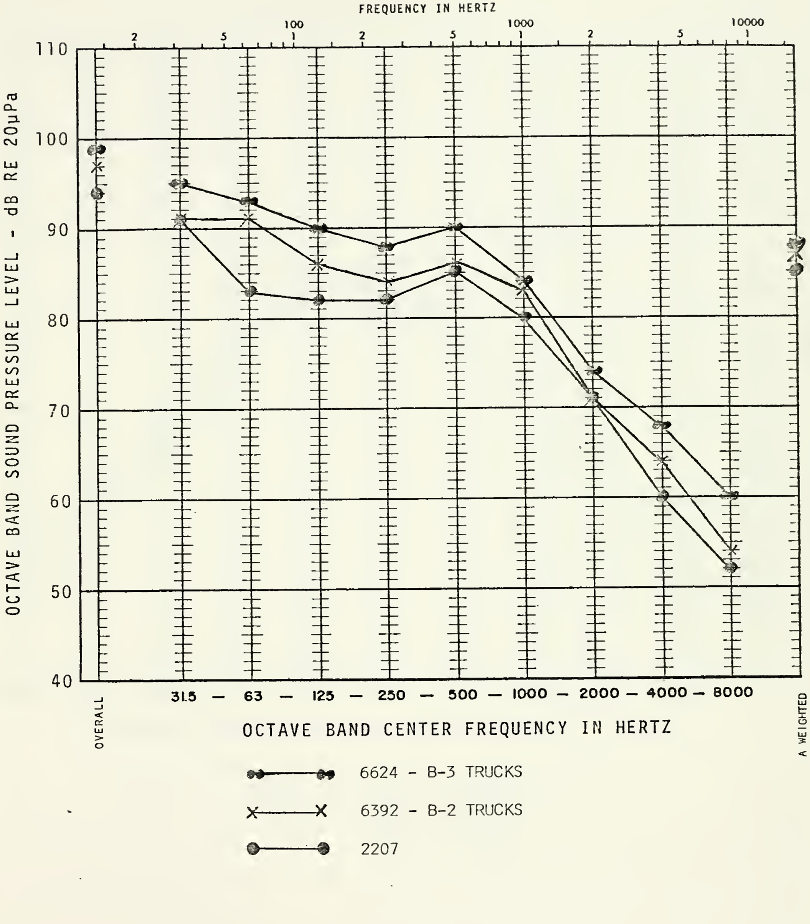


FIGURE E9 AVERAGE CAR INTERIOR NOISE LEVELS ON 4-TRACK ON SOLID WEB ELEVATED STRUCTURE

40 MPH

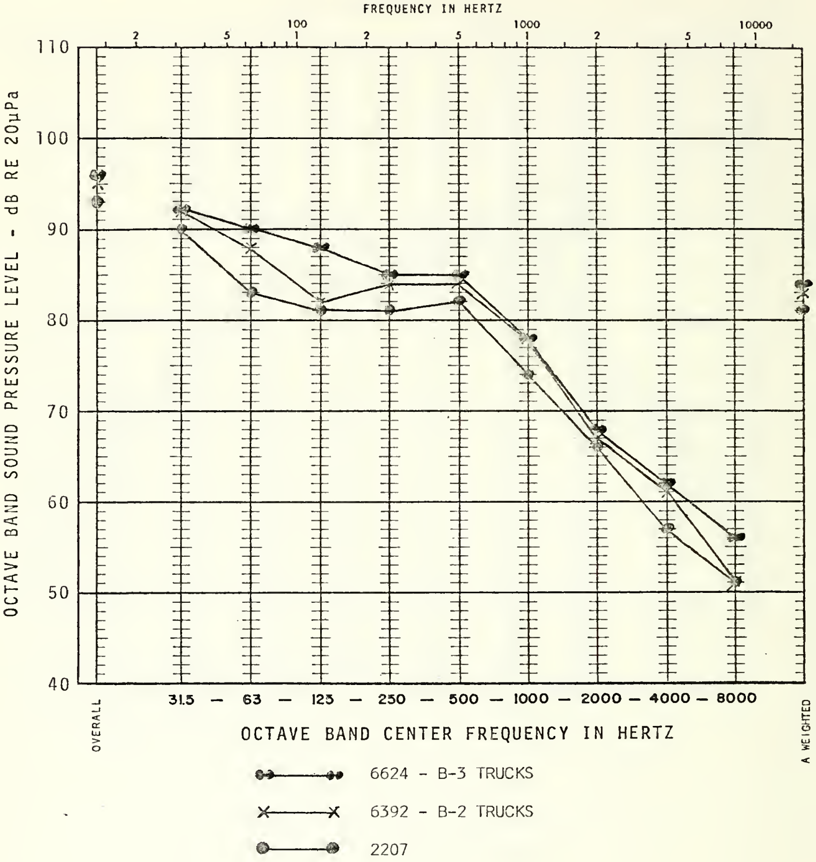


FIGURE E10 AVERAGE CAR INTERIOR NOISE LEVELS ON 4-TRACK SOLID WEB ELEVATED STRUCTURE

30 MPH

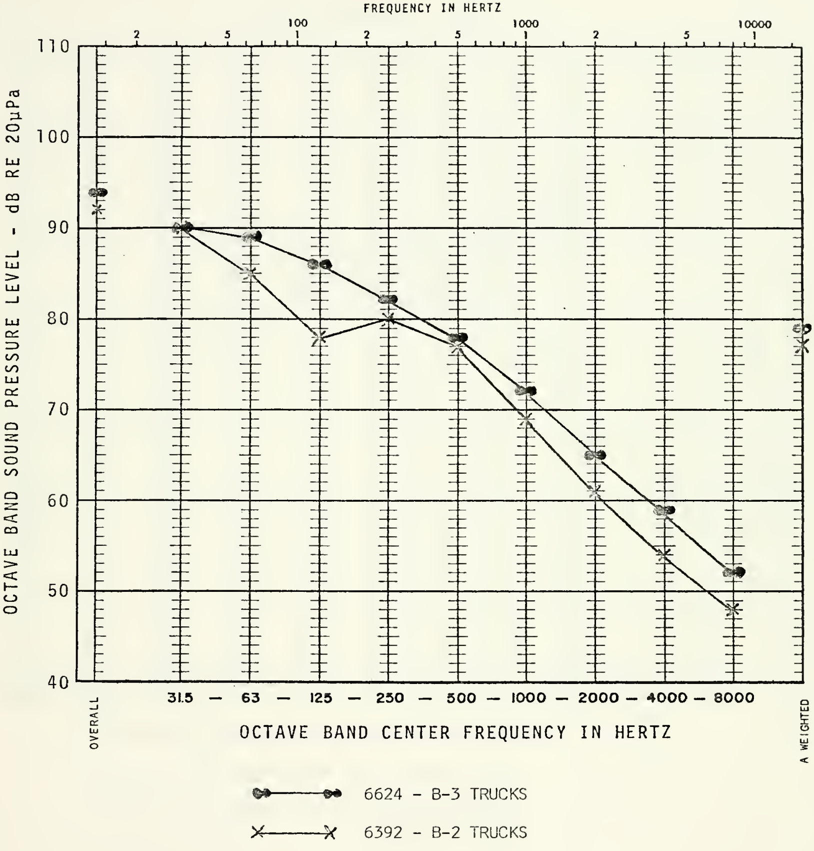


FIGURE E11 AVERAGE CAR INTERIOR NOISE LEVELS ON 4-TRACK SOLID WEB ELEVATED STRUCTURE

20 MPH

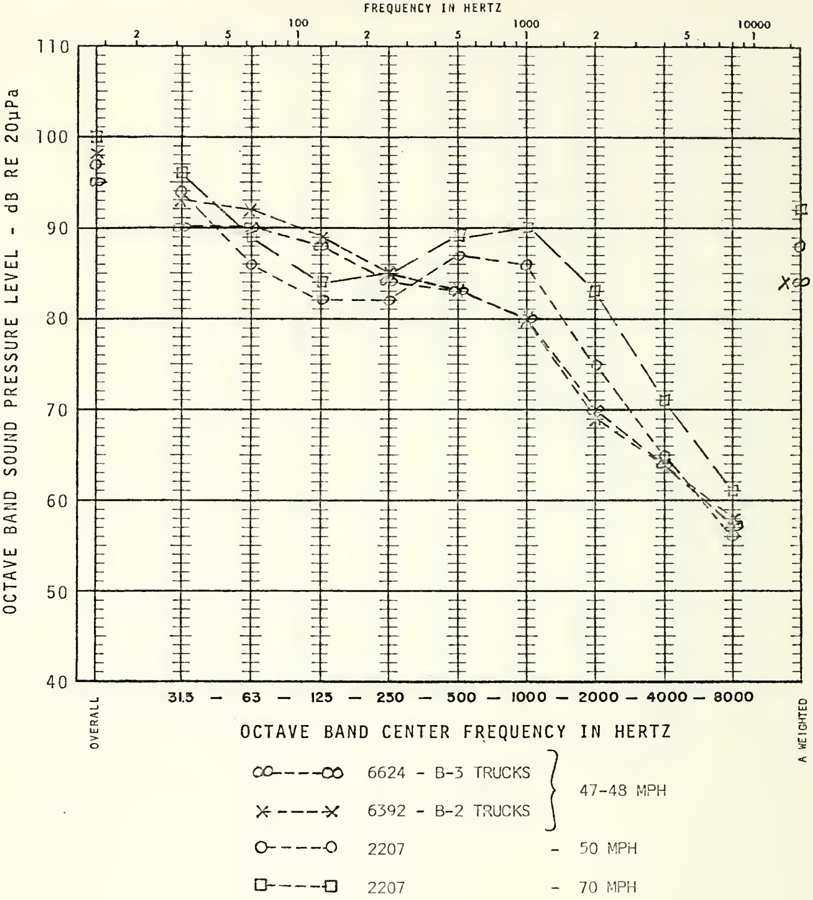


FIGURE E12 AVERAGE CAR INTERIOR NOISE LEVELS ON BALLAST AND TIE TRACKS

JOINTED RAIL

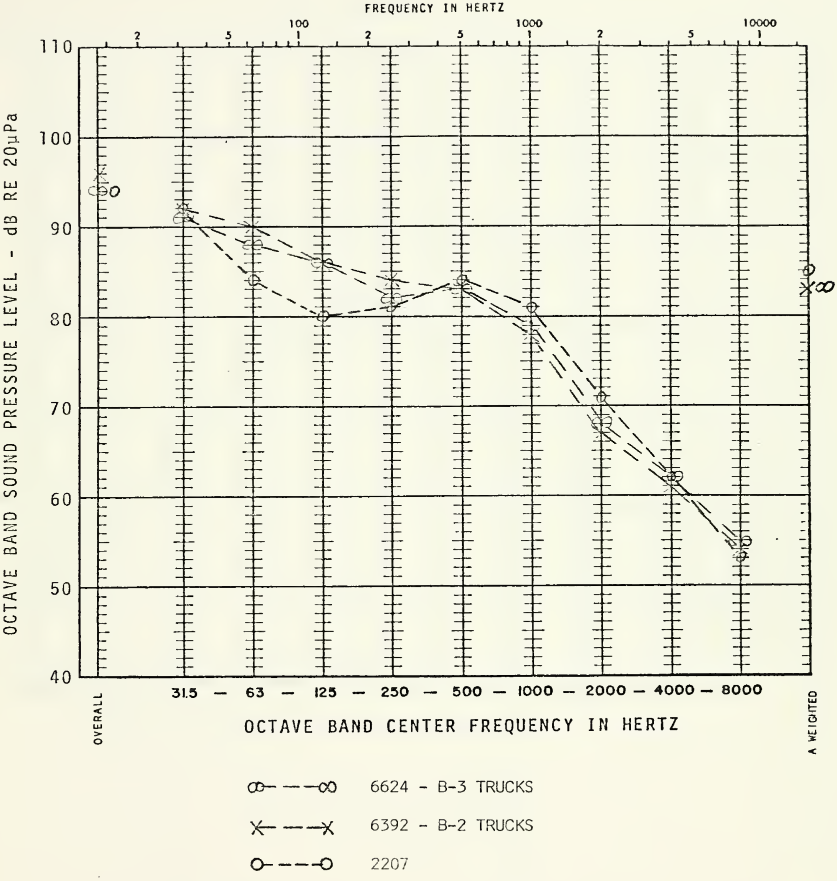


FIGURE E13 AVERAGE CAR INTERIOR NOISE LEVELS ON BALLAST & TIE TRACKS

JOINTED RAIL - 40 MPH

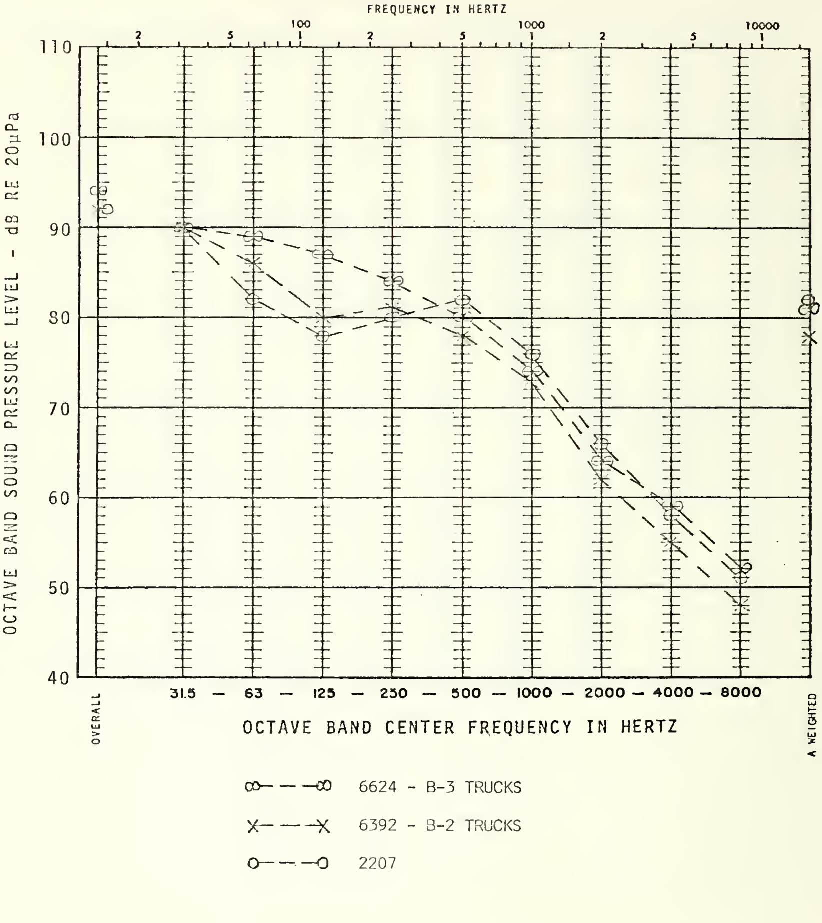
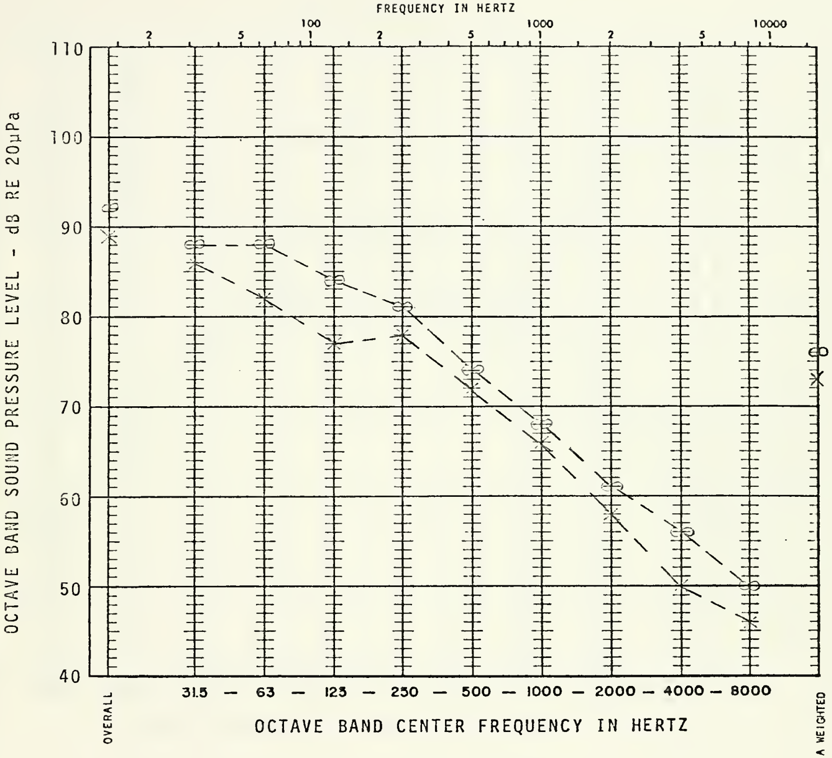


FIGURE E14 AVERAGE CAR INTERIOR NOISE LEVELS ON BALLAST & TIE TRACKS

JOINTED RAIL - 30 MPH



ꝏ— — —ꝏ 6624 - B-3 TRUCKS

X— — —X 6392 - B-2 TRUCKS

FIGURE E15 AVERAGE CAR INTERIOR NOISE LEVELS ON BALLAST & TIE TRACKS

JOINTED RAIL - 20 MPH

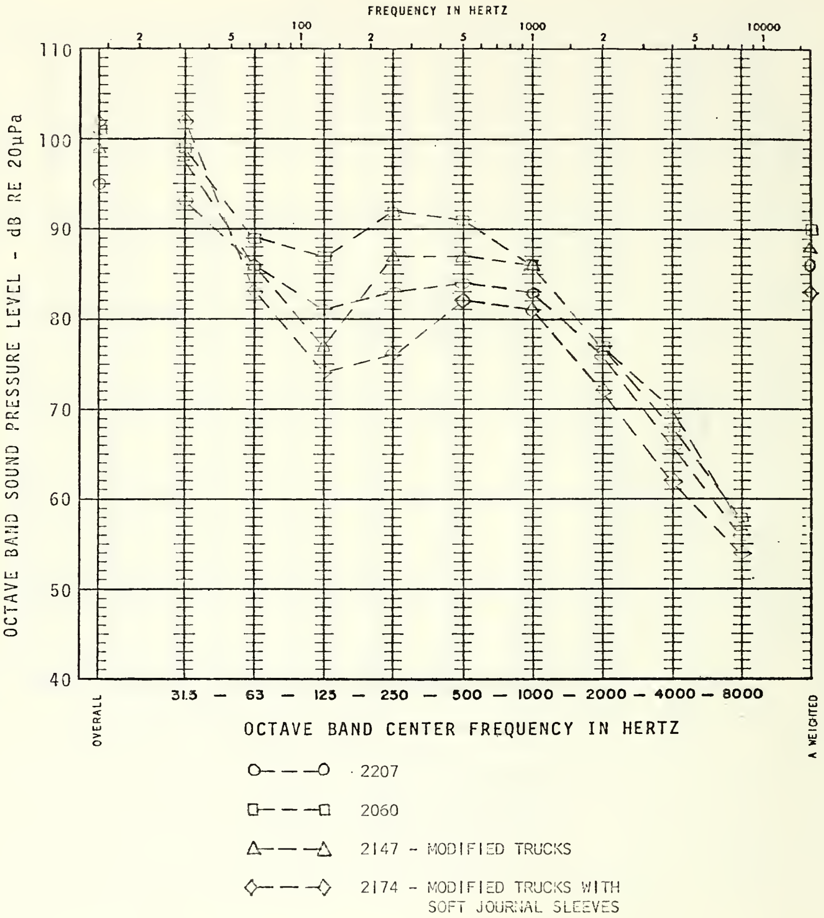


FIGURE E16 AVERAGE CAR INTERIOR NOISE LEVELS ON BALLAST & TIE TRACKS

WORN CONTINUOUS WELDED RAIL - 60 MPH

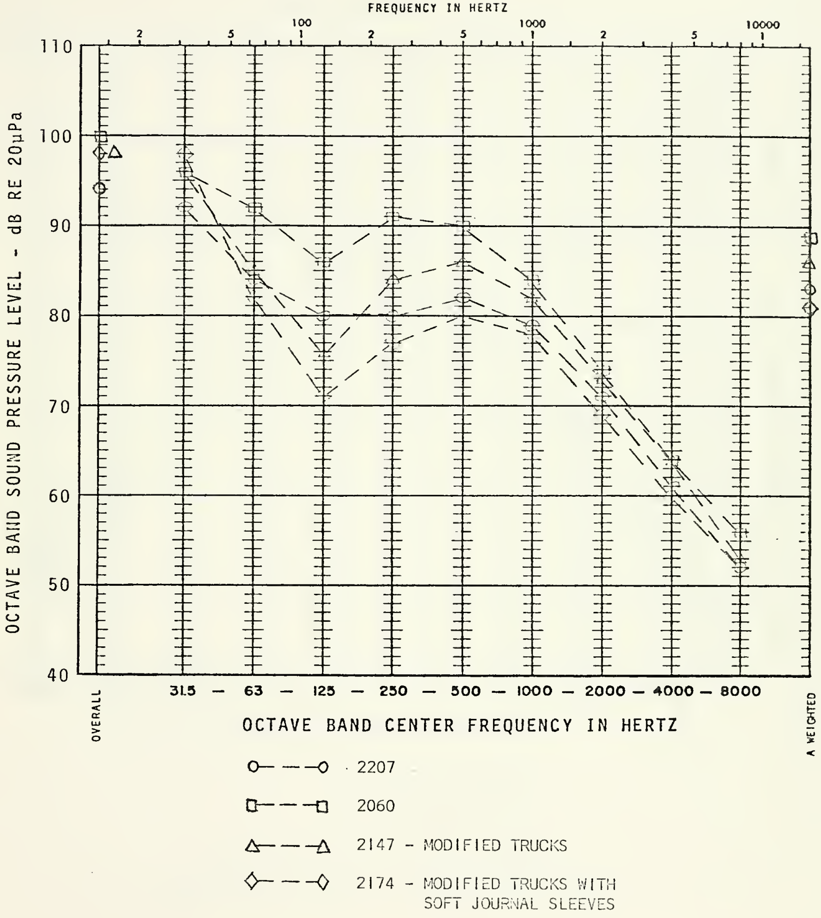


FIGURE E17 AVERAGE CAR INTERIOR NOISE LEVELS ON BALLAST & TIE TRACKS

WORN CONTINUOUS WELDED RAIL - 50 MPH

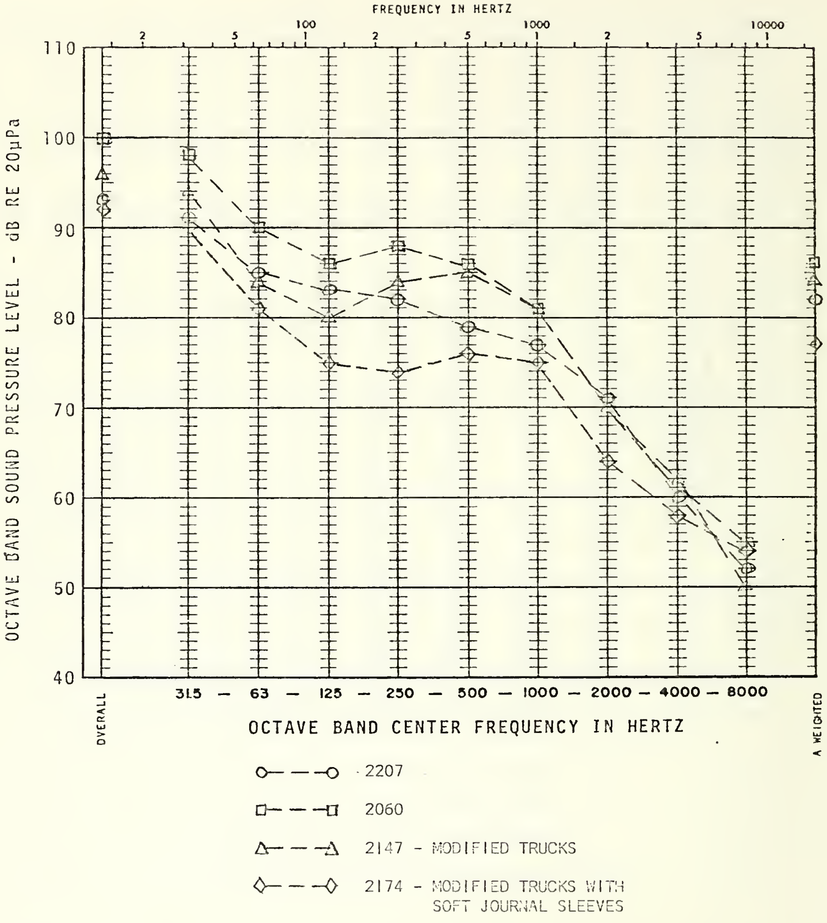


FIGURE E18 AVERAGE CAR INTERIOR NOISE LEVELS ON BALLAST & TIE TRACKS

WORN CONTINUOUS WELDED RAIL - 40 MPH

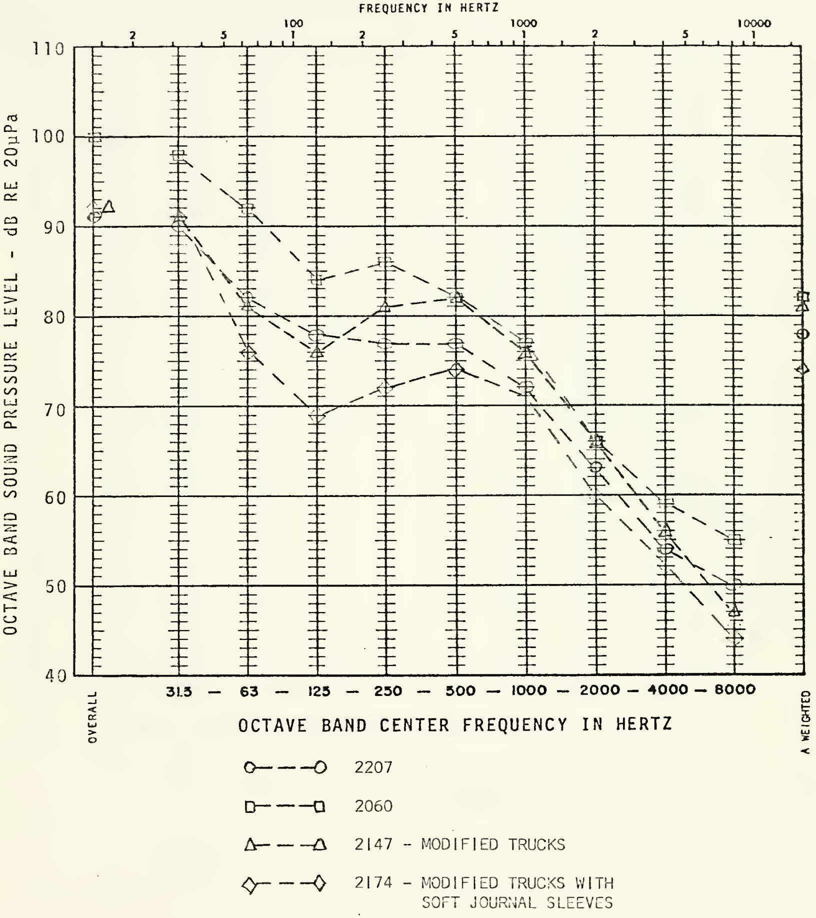


FIGURE E19 AVERAGE CAR INTERIOR NOISE LEVELS ON BALLAST & TIE TRACKS

WORN CONTINUOUS WELDED RAIL - 30 MPH

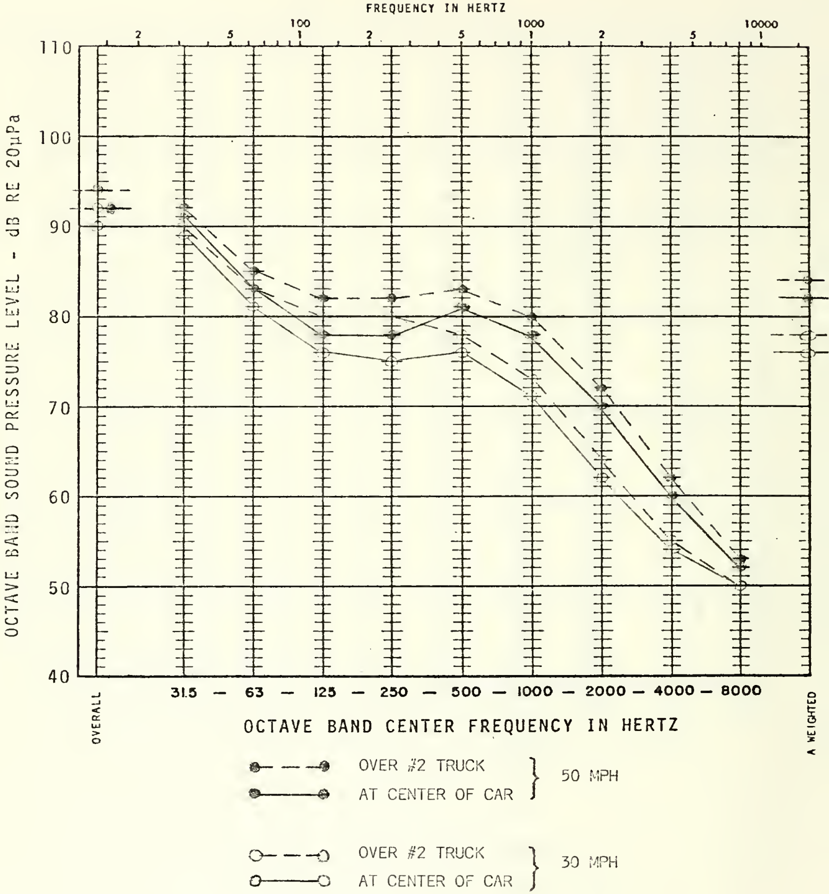


FIGURE E20 INTERIOR NOISE LEVELS FOR CAR 2207 ON WORN CONTINUOUS WELDED RAIL - BALLAST & TIE AT GRADE TRACKS

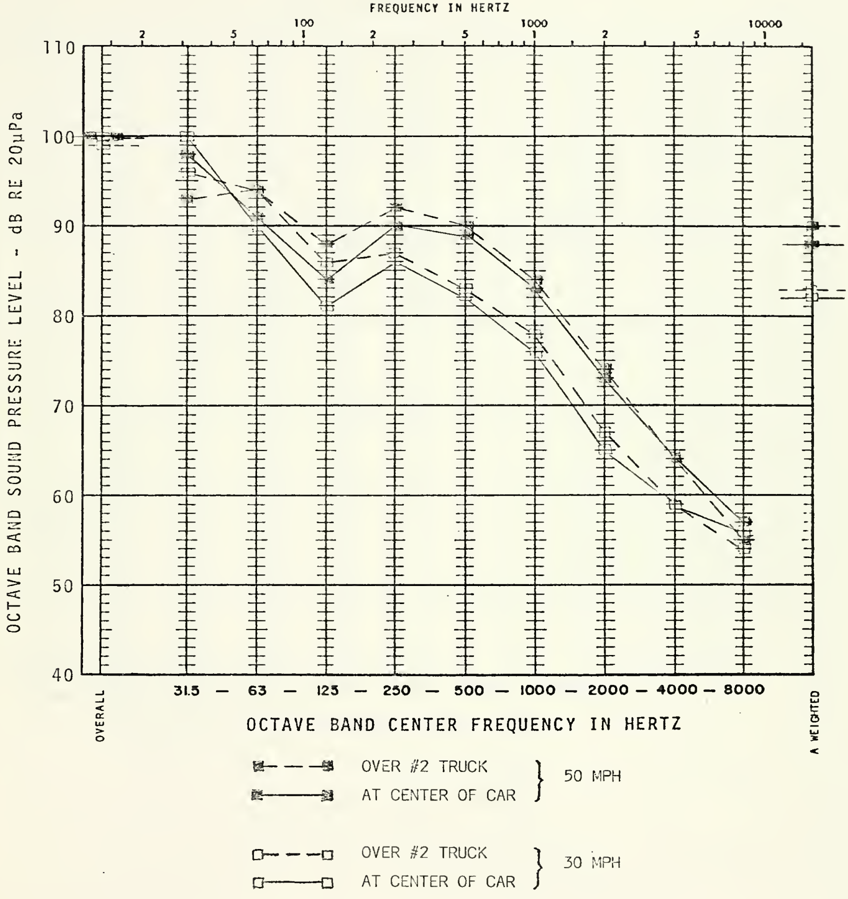


FIGURE E21 INTERIOR NOISE LEVELS FOR CAR 2060 ON WORN CONTINUOUS WELDED RAIL - BALLAST & TIE AT GRADE TRACKS

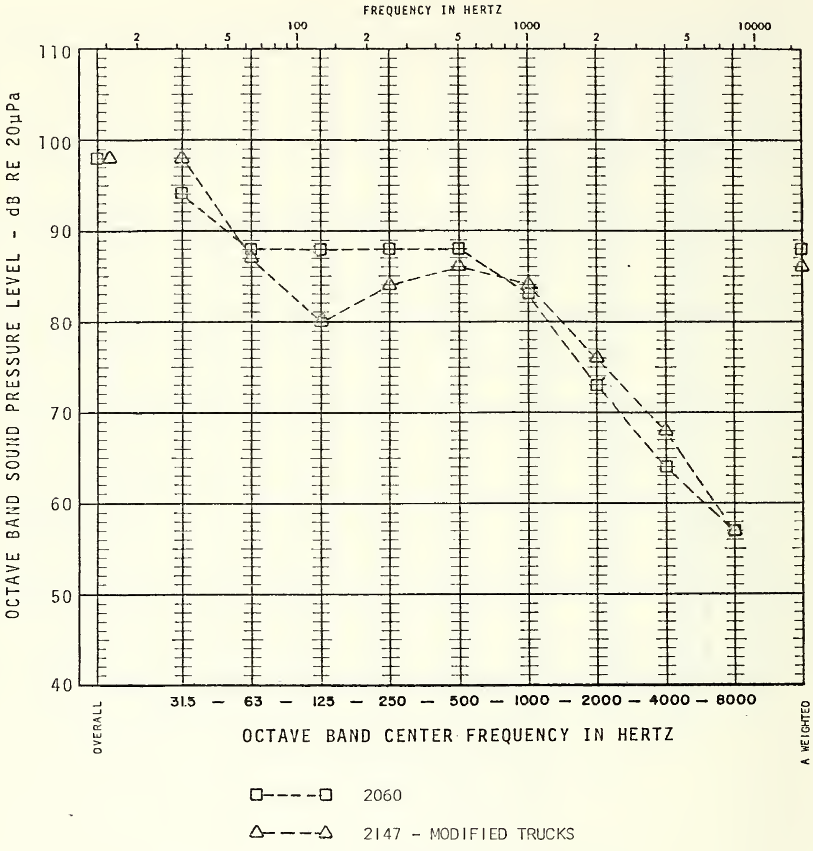


FIGURE E22 AVERAGE CAR INTERIOR NOISE LEVELS ON BALLAST AND TIE TRACKS

SMOOTH CONTINUOUS WELDED RAIL - 60 MPH

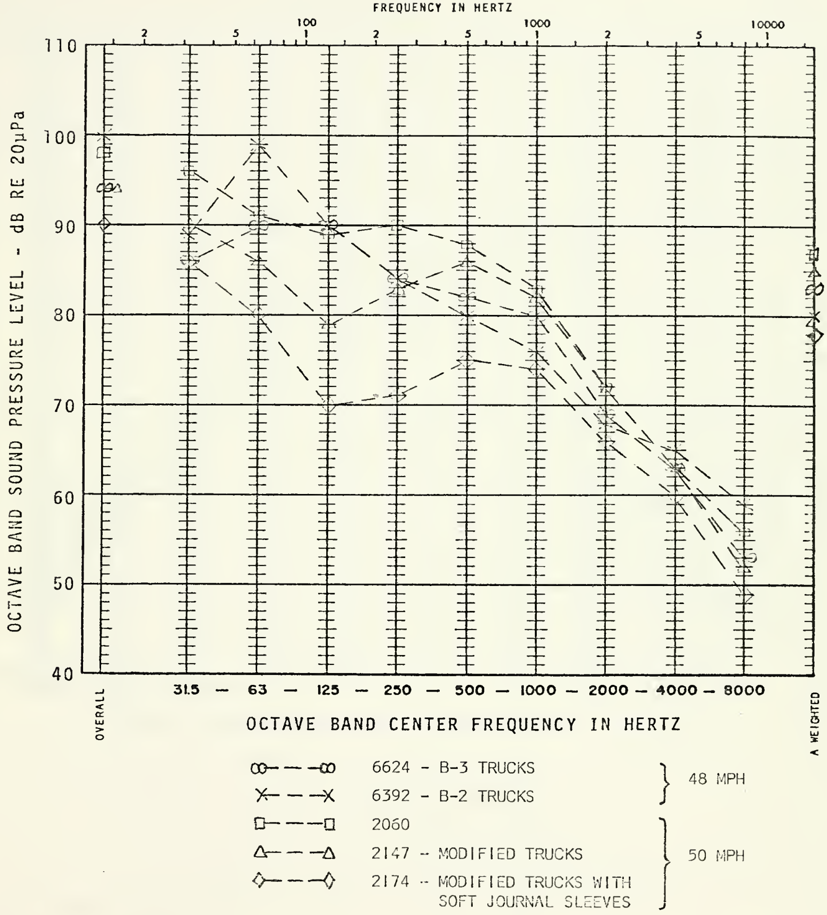


FIGURE E23 AVERAGE CAR INTERIOR NOISE LEVELS ON BALLAST & TIE TRACKS

SMOOTH CONTINUOUS WELDED RAIL - 50 MPH

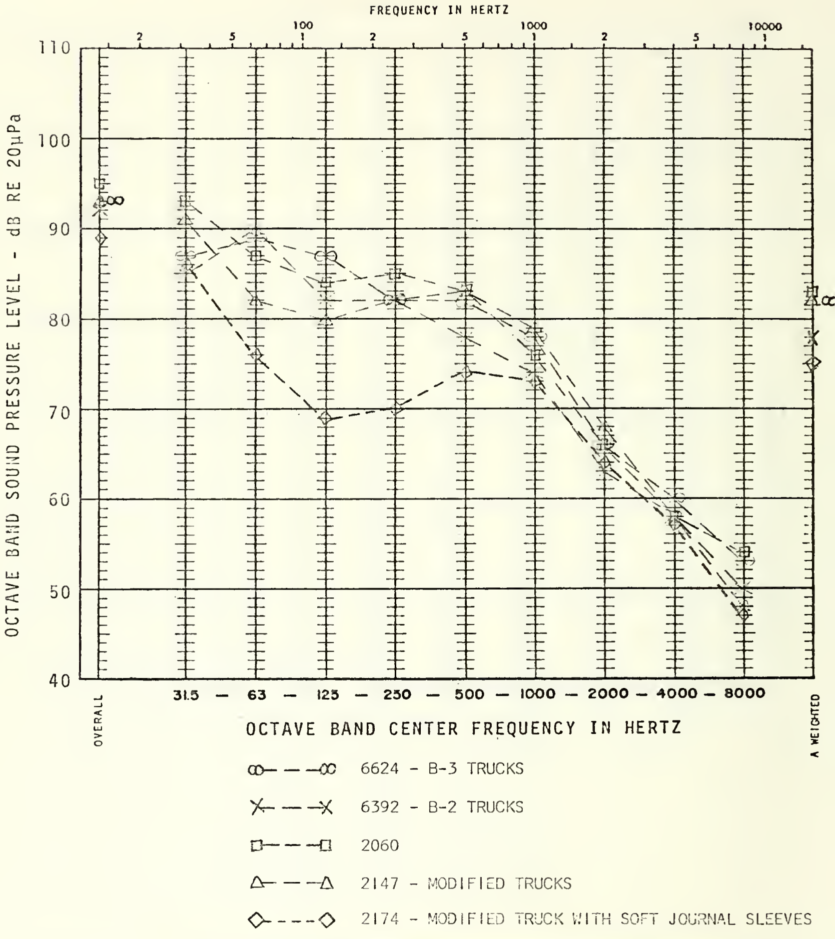


FIGURE E24 AVERAGE CAR INTERIOR NOISE LEVELS ON BALLAST & TIE TRACKS

SMOOTH CONTINUOUS WELDED RAIL - 40 MPH

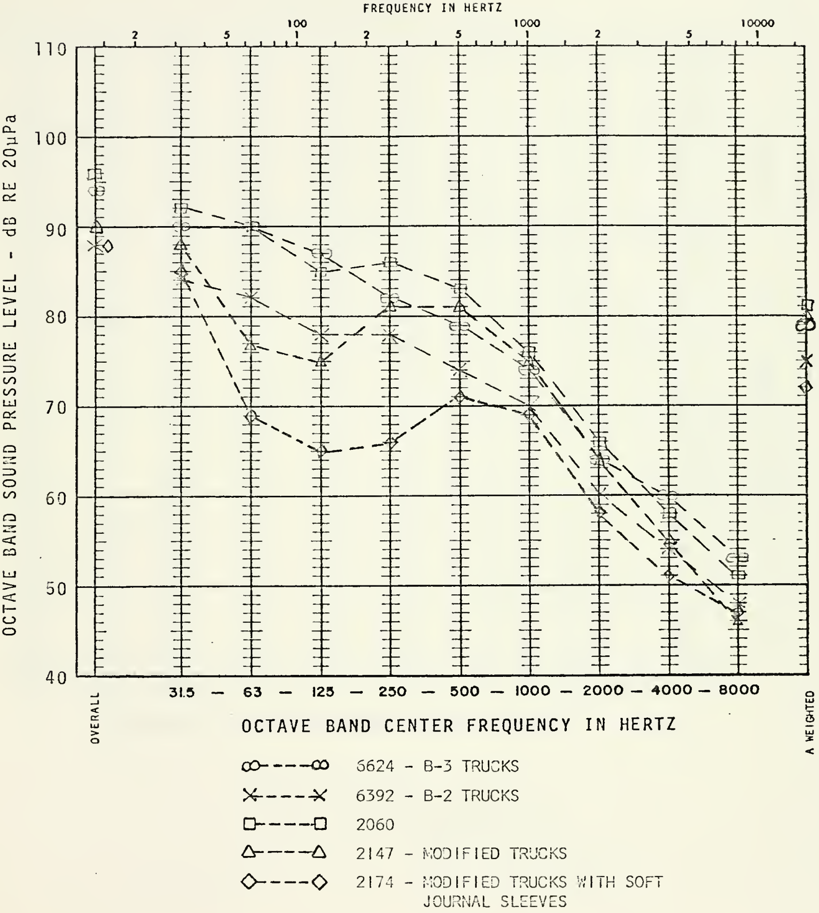


FIGURE E25 AVERAGE CAR INTERIOR NOISE LEVELS ON BALLAST & TIE TRACKS

SMOOTH CONTINUOUS WELDED RAIL - 30 MPH

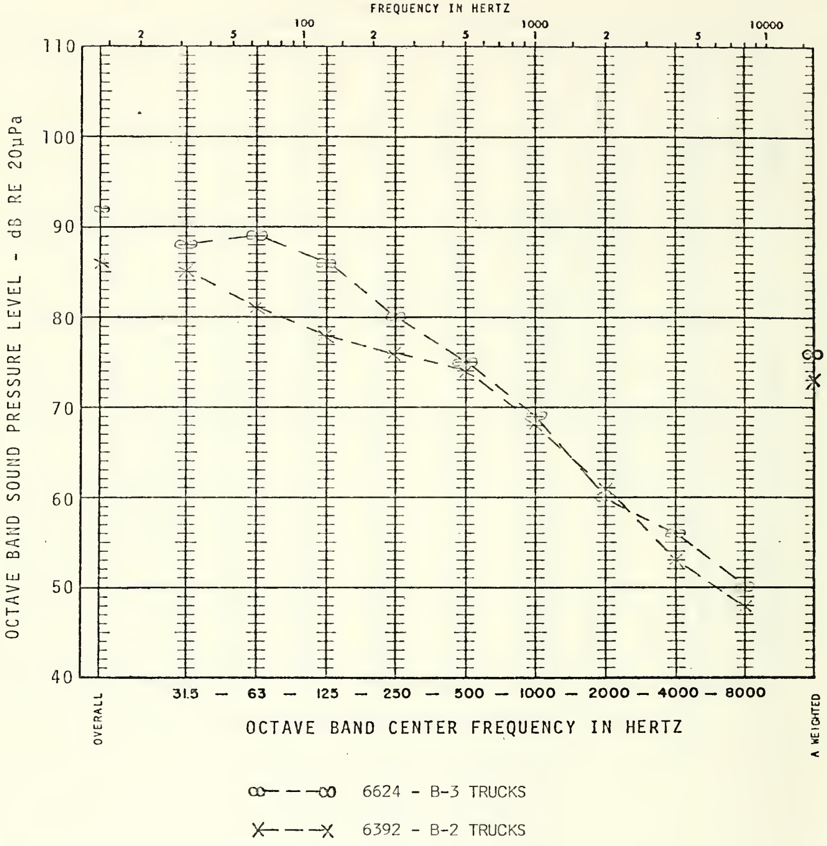


FIGURE E26 AVERAGE CAR INTERIOR NOISE LEVELS ON BALLAST & TIE TRACKS

SMOOTH CONTINUOUS WELDED RAIL - 20 MPH

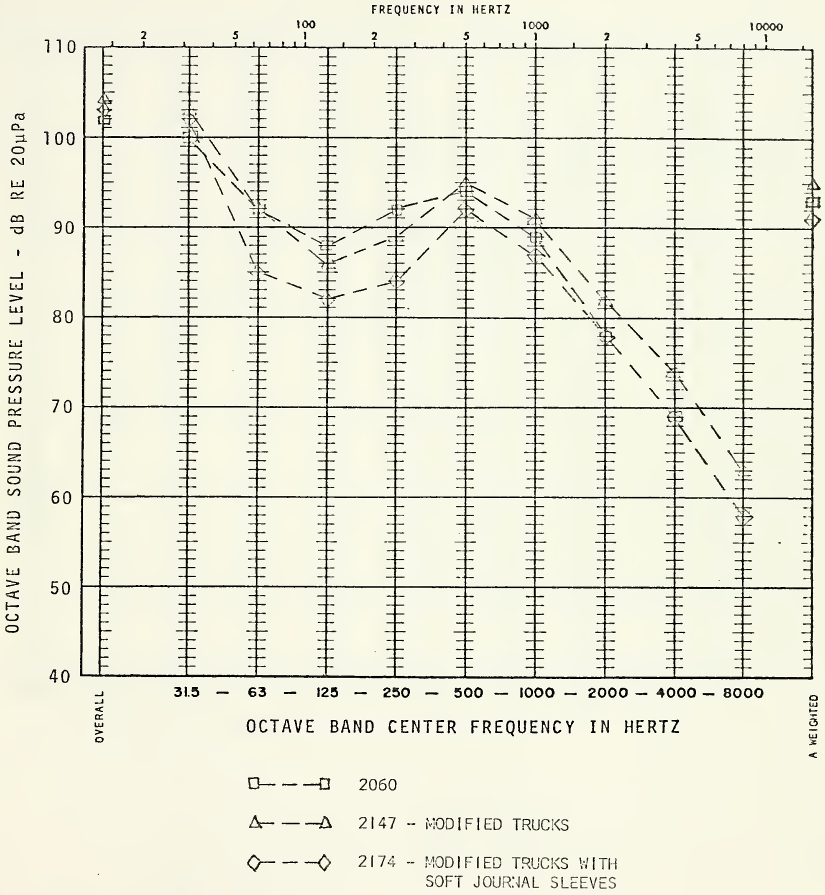


FIGURE E27 AVERAGE CAR INTERIOR NOISE LEVELS ON BALLAST & TIE TRACKS

AT CROSSOVER - 60 MPH

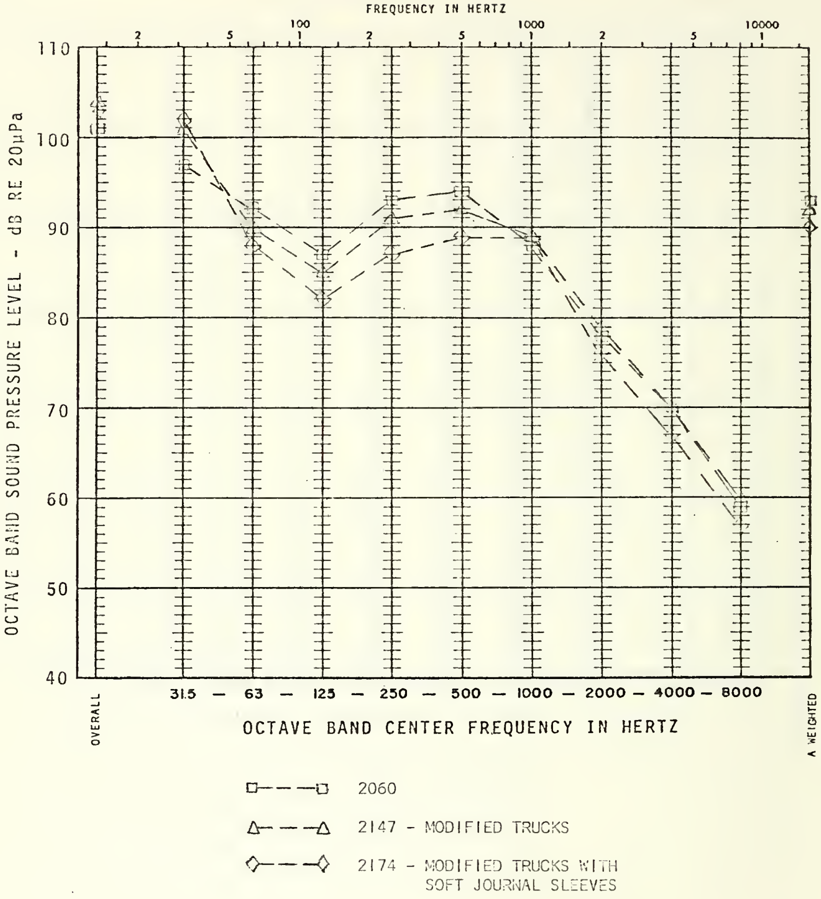


FIGURE E28 AVERAGE CAR INTERIOR NOISE LEVELS ON BALLAST & TIE TRACKS

AT CROSSOVER - 50 MPH

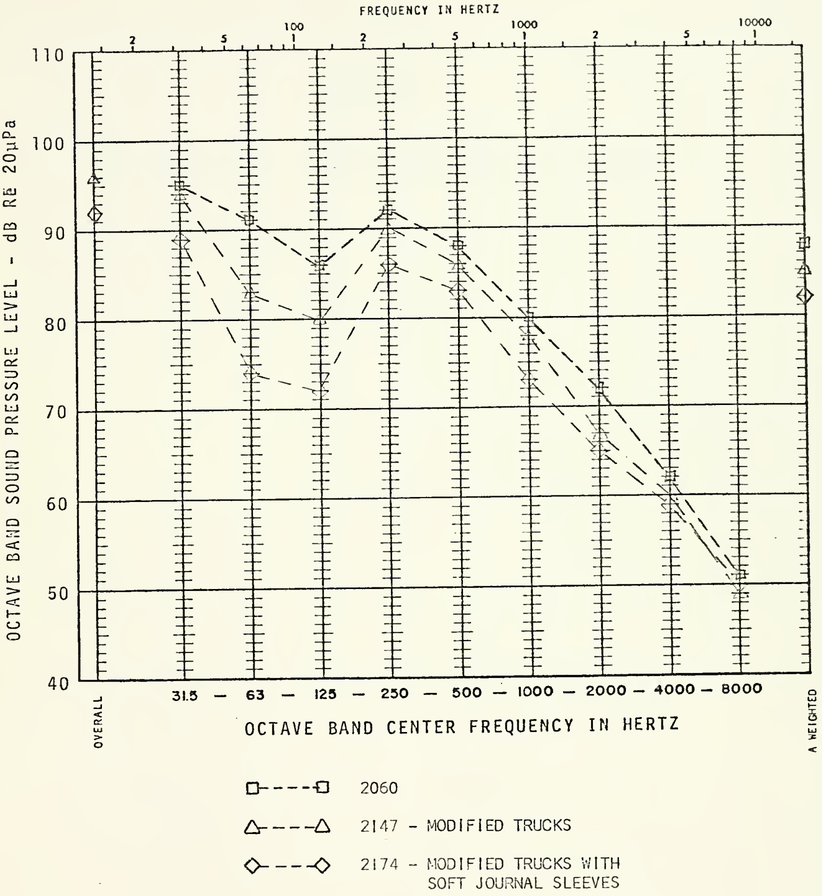


FIGURE E29 AVERAGE CAR INTERIOR NOISE LEVELS ON BALLAST & TIE TRACKS

AT CROSSOVER - 30 MPH

APPENDIX F

CAR INTERIOR NOISE LEVELS FOR OPERATION IN SUBWAYS

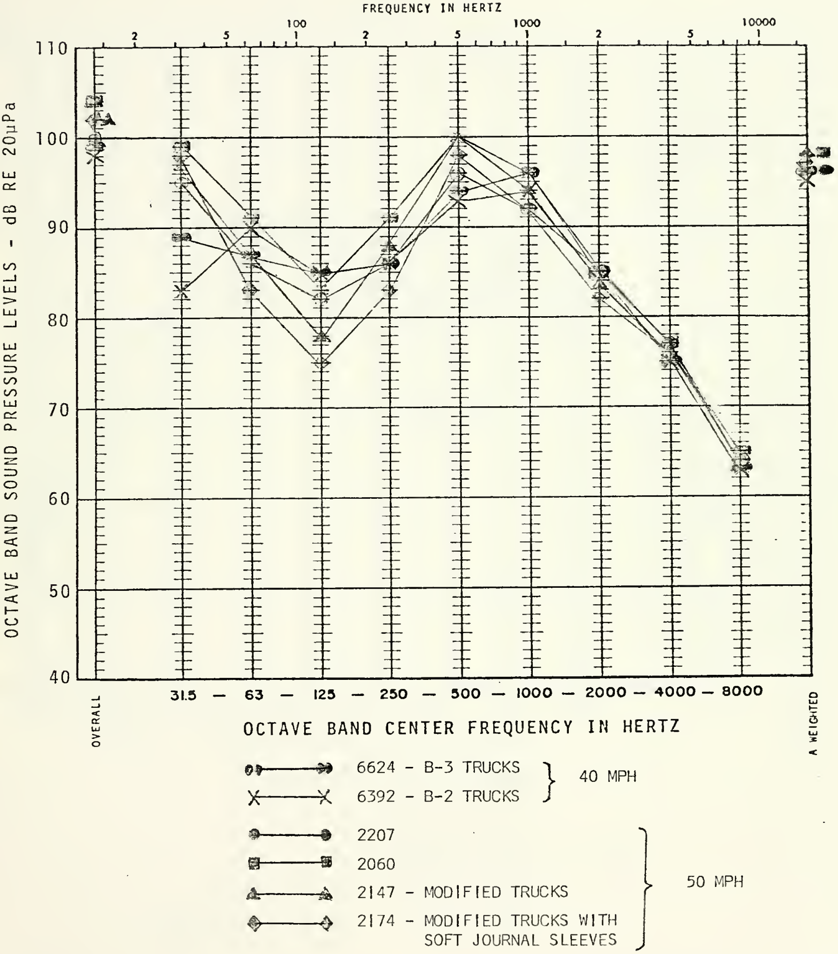


FIGURE F1 AVERAGE CAR INTERIOR NOISE LEVELS IN ROUND TUNNEL WITH CONCRETE TRACKBED

40 MPH & 50 MPH

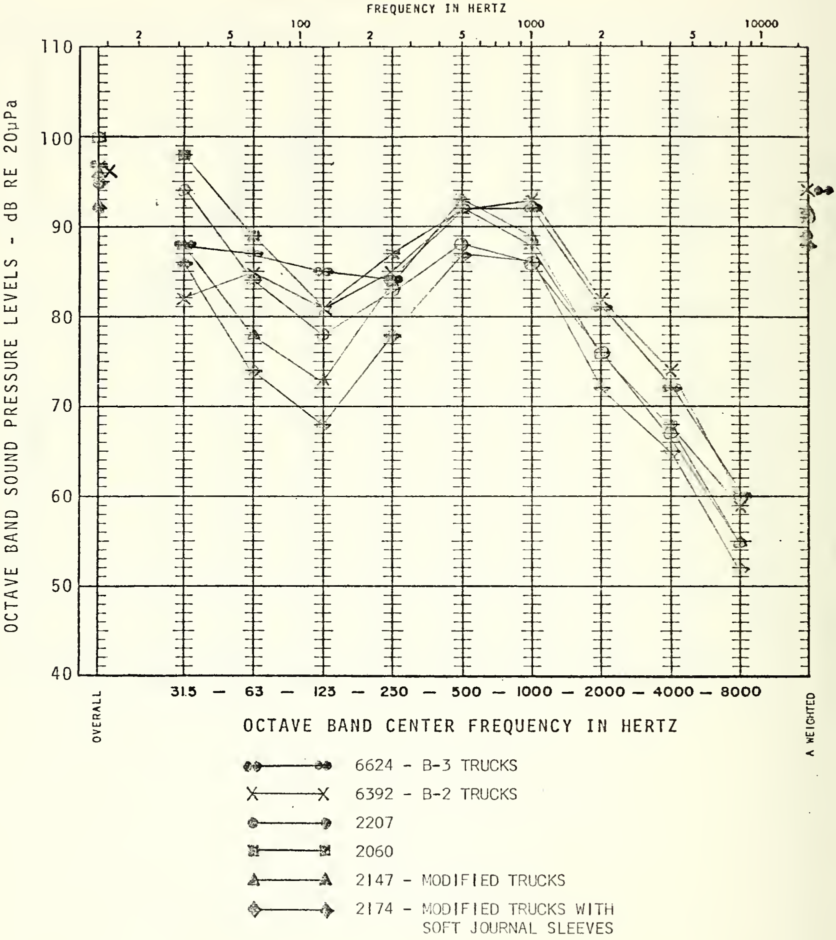


FIGURE F2 AVERAGE CAR INTERIOR NOISE LEVELS IN ROUND TUNNEL WITH CONCRETE TRACKBED

30 MPH

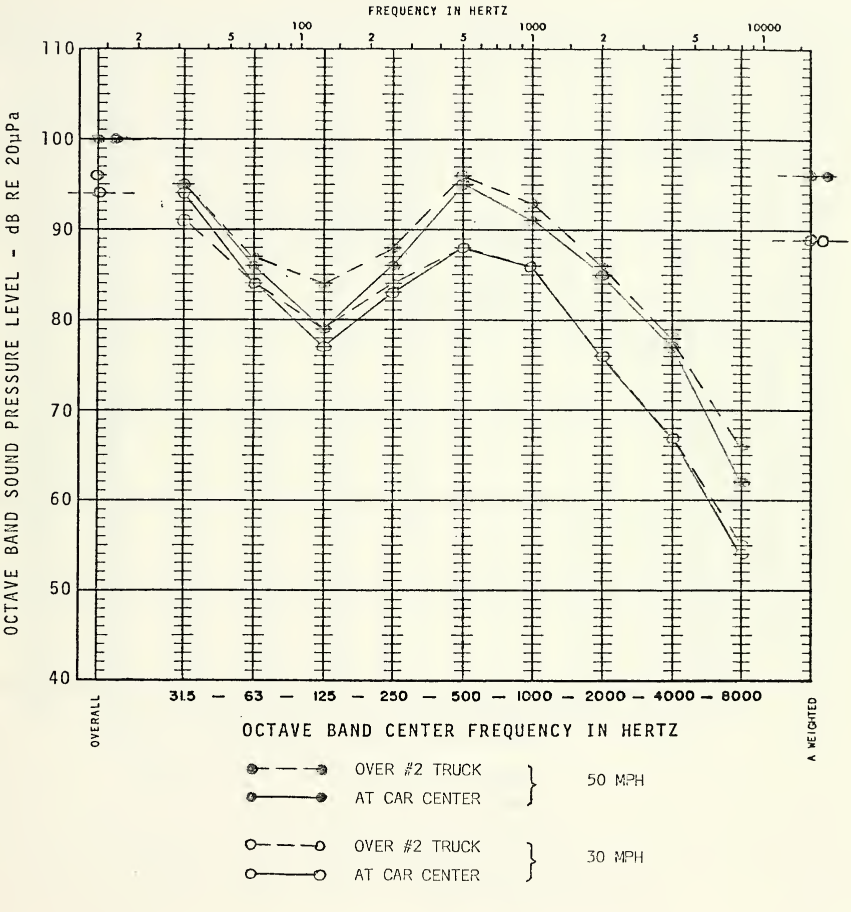


FIGURE F3 INTERIOR NOISE LEVELS IN CAR 2207 IN ROUND TUNNEL WITH CONCRETE TRACKBED

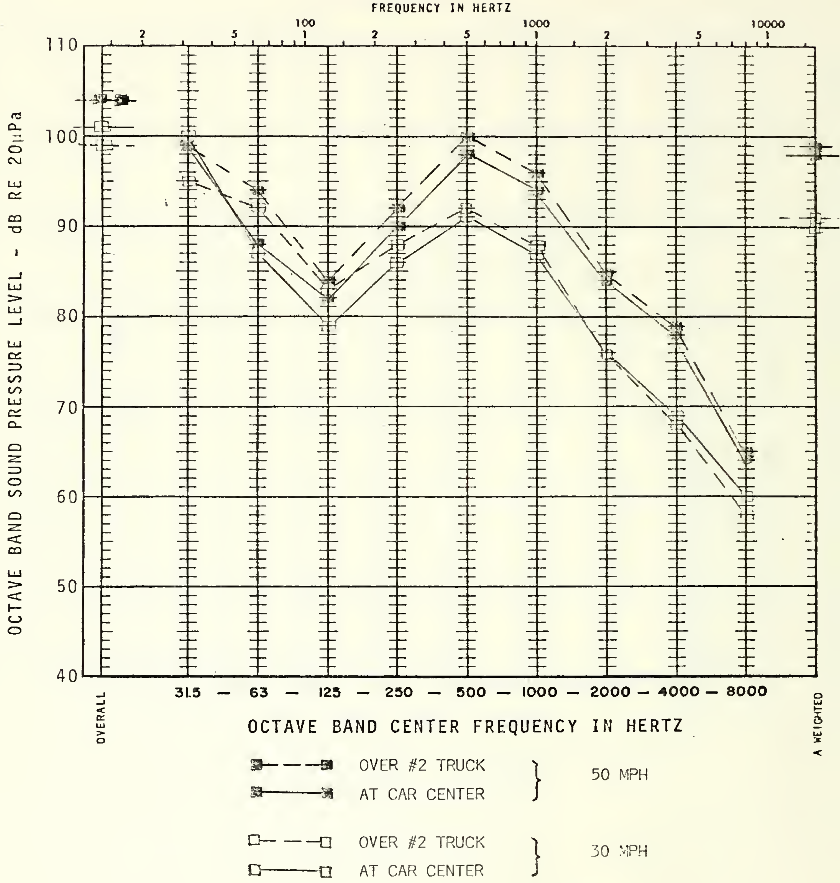


FIGURE F4 INTERIOR NOISE LEVELS IN CAR 2060 IN ROUND TUNNEL WITH CONCRETE TRACKBED

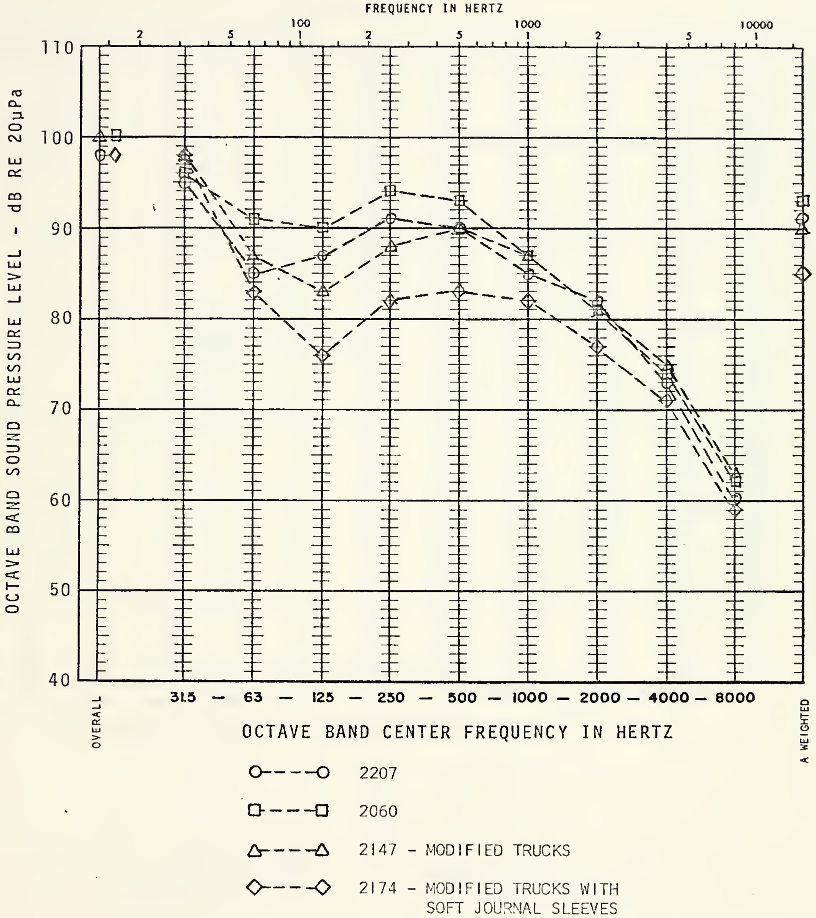


FIGURE F5 AVERAGE CAR INTERIOR NOISE LEVELS IN ROUND TUNNEL WITH BALLAST AND TIE TRACK

50 MPH

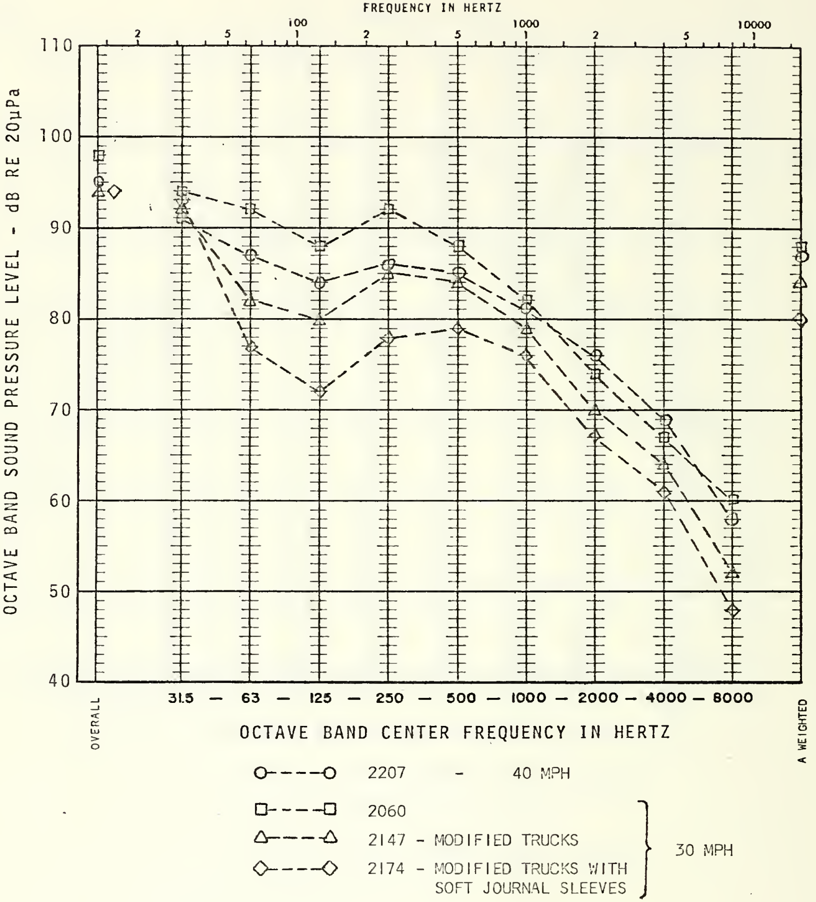


FIGURE F6 AVERAGE CAR INTERIOR NOISE LEVELS IN ROUND TUNNEL WITH BALLAST AND TIE TRACK

30 MPH & 40 MPH

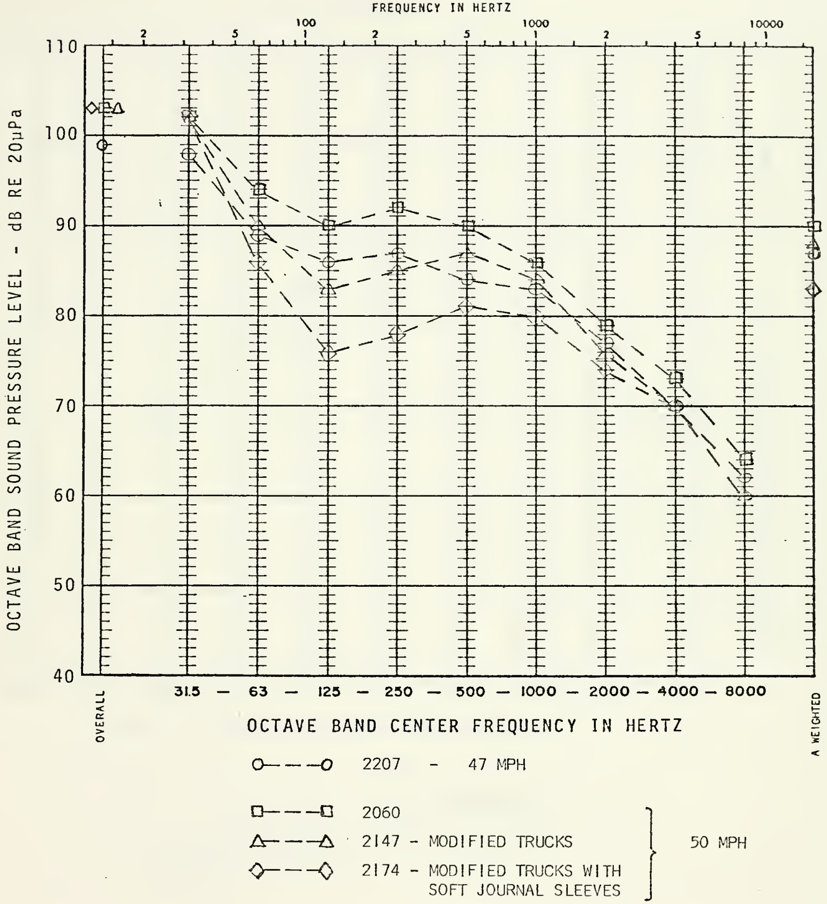


FIGURE F7 AVERAGE CAR INTERIOR NOISE LEVELS IN BOX SECTION SUBWAY WITH BALLAST & TIE TRACK

50 MPH

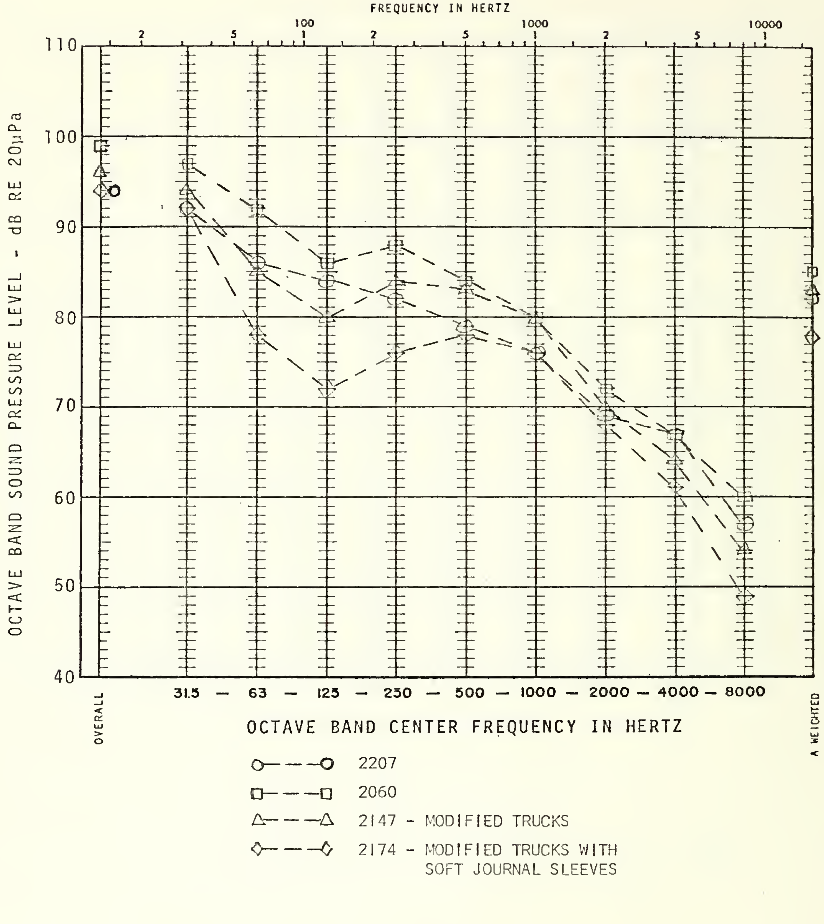


FIGURE F8 AVERAGE CAR INTERIOR NOISE LEVELS IN BOX SECTION SUBWAY WITH BALLAST & TIE TRACK

30 MPH

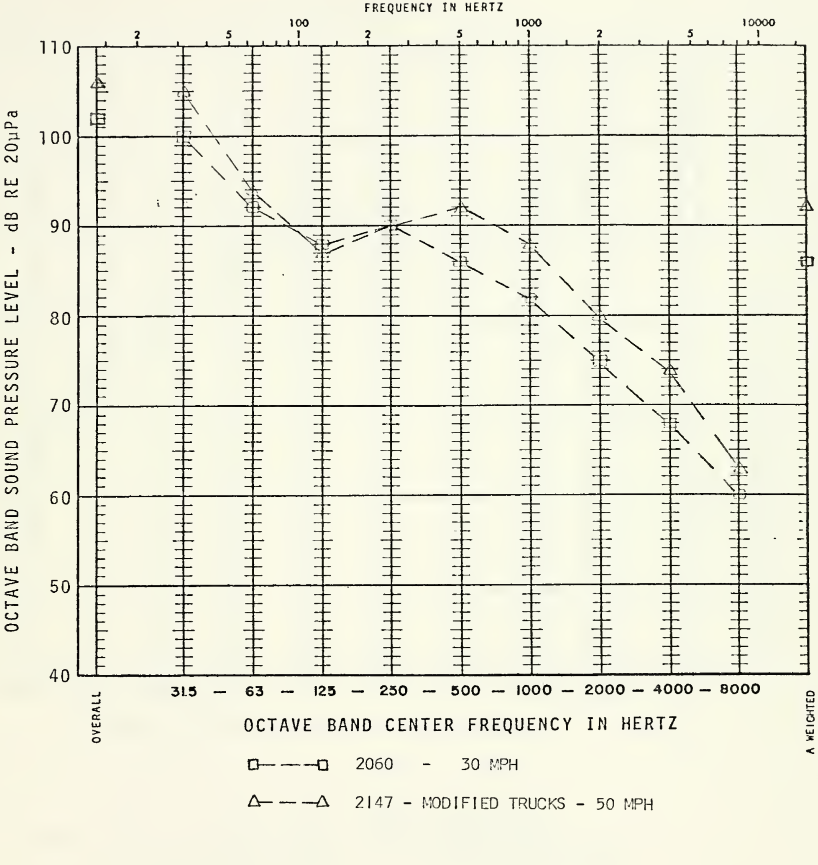


FIGURE F9 AVERAGE CAR INTERIOR NOISE LEVELS AT A CROSSOVER IN ROUND TUNNEL

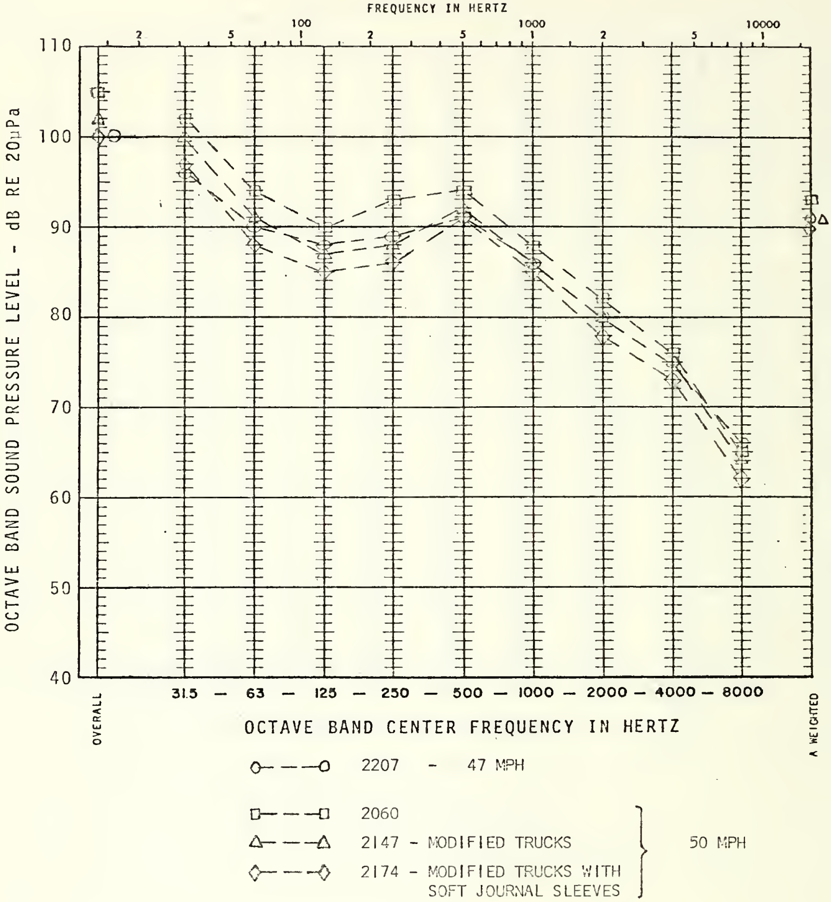


FIGURE F10 AVERAGE CAR INTERIOR NOISE LEVELS AT A CROSSOVER IN BOX SECTION SUBWAY

50 MPH

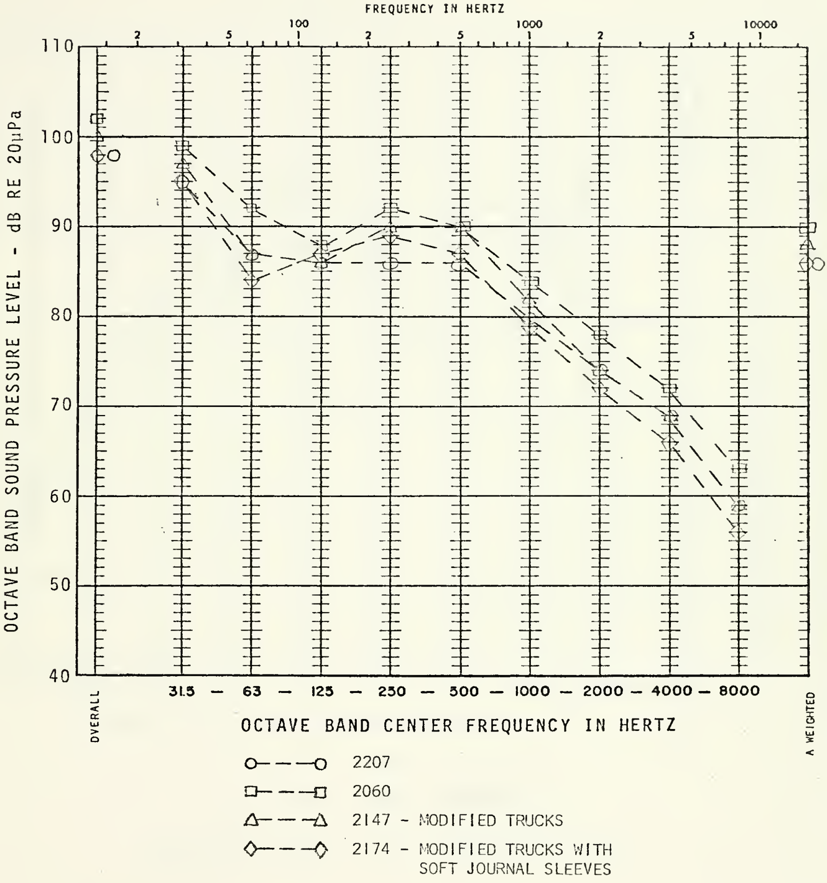


FIGURE F11 AVERAGE CAR INTERIOR NOISE LEVELS AT A CROSSOVER IN BOX SECTION SUBWAY

30 MPH

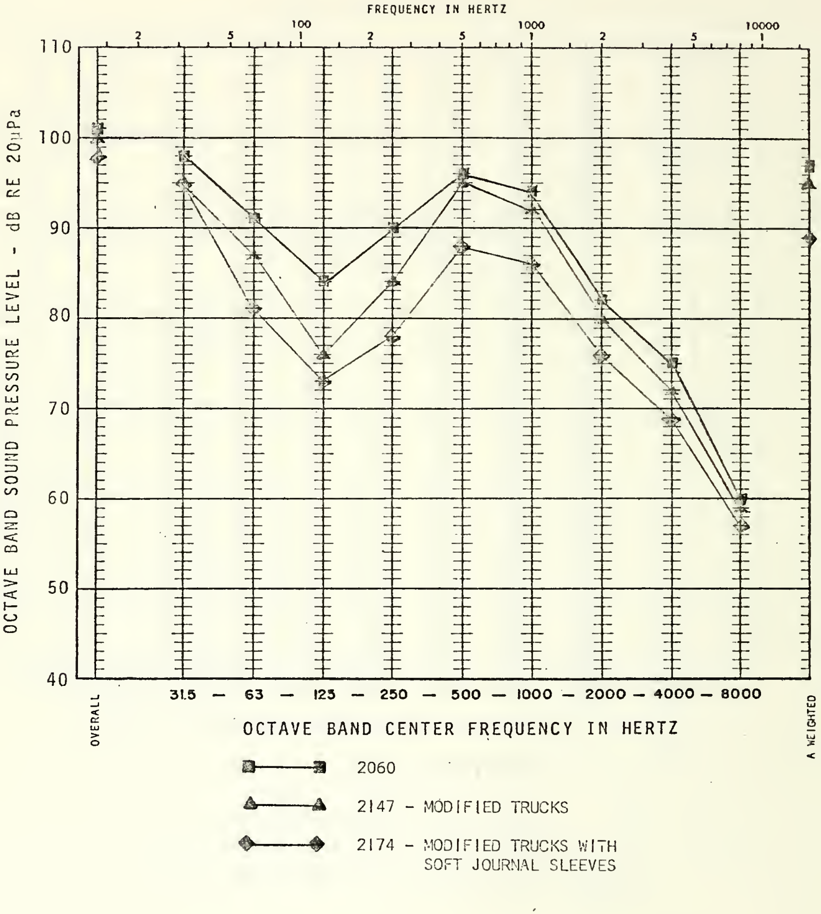


FIGURE F12 AVERAGE CAR INTERIOR NOISE LEVELS WHEN PASSING THROUGH A ROUND TUNNEL STATION WITH CONCRETE TRACKBED

50 MPH

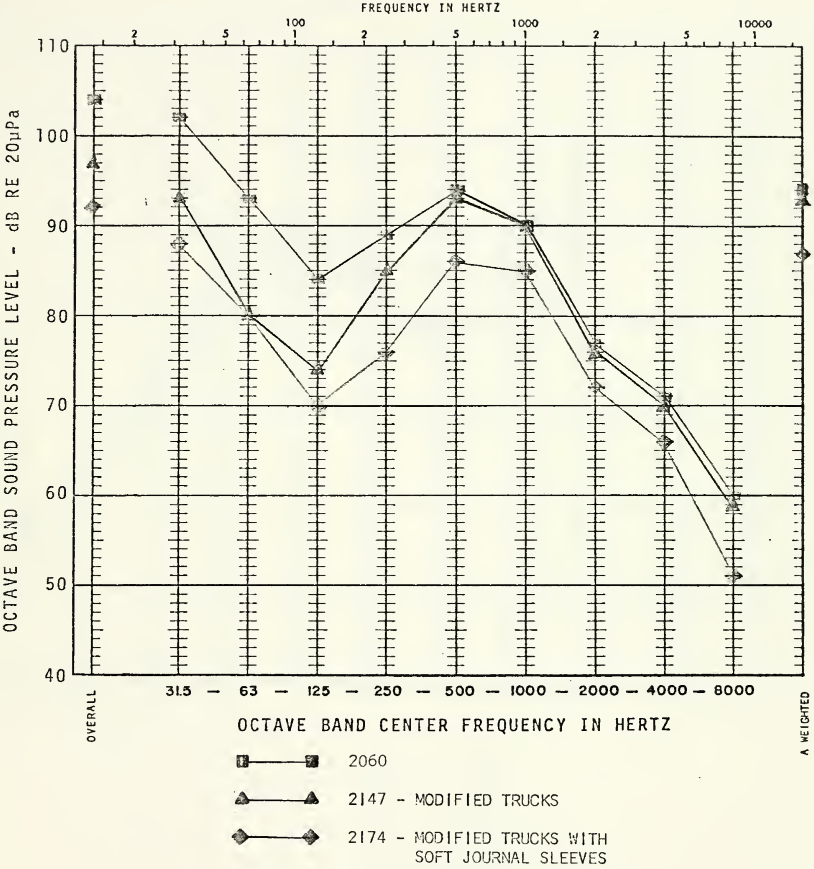


FIGURE F13 AVERAGE CAR INTERIOR NOISE LEVELS WHEN PASSING THROUGH A ROUND TUNNEL STATION WITH CONCRETE TRACKBED

40 MPH

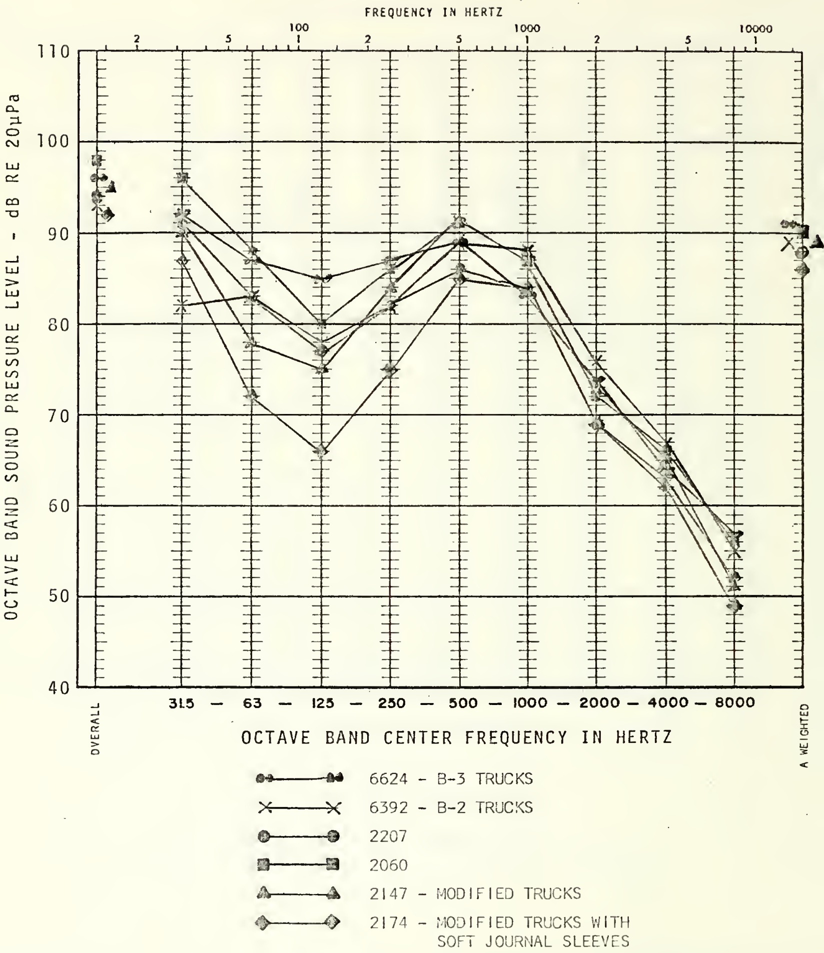
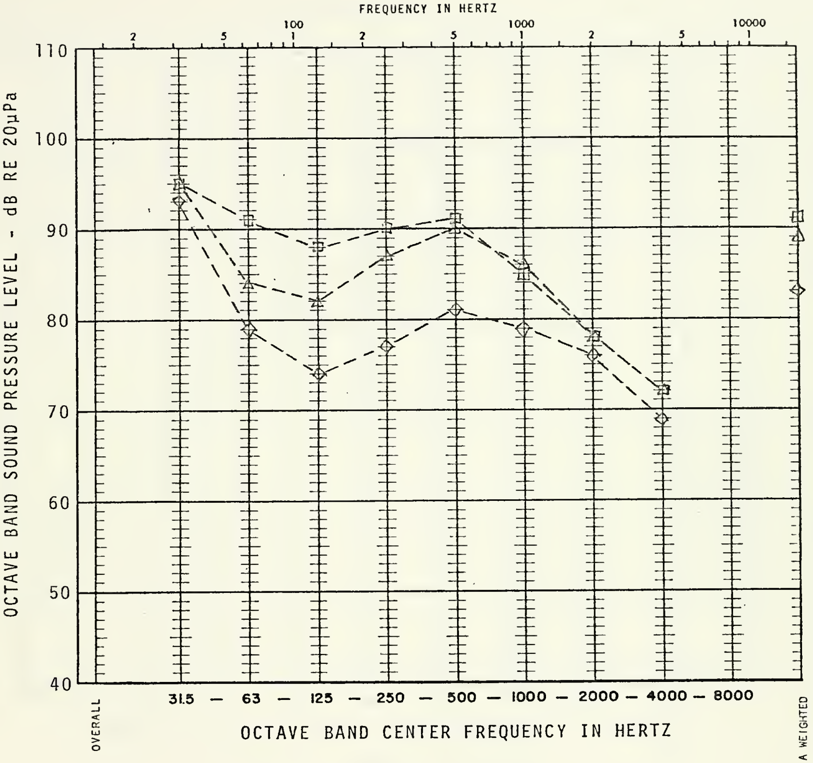


FIGURE F14 AVERAGE CAR INTERIOR NOISE LEVELS WHEN PASSING THROUGH A ROUND TUNNEL STATION WITH CONCRETE TRACKBED

30 MPH



□----□ 2060

△----△ 2147 - MODIFIED TRUCKS

◇----◇ 2174 - MODIFIED TRUCKS WITH SOFT JOURNAL SLEEVES

FIGURE F15 AVERAGE CAR INTERIOR NOISE LEVELS WHEN PASSING THROUGH A ROUND TUNNEL STATION WITH BALLAST AND TIE TRACK

50 MPH

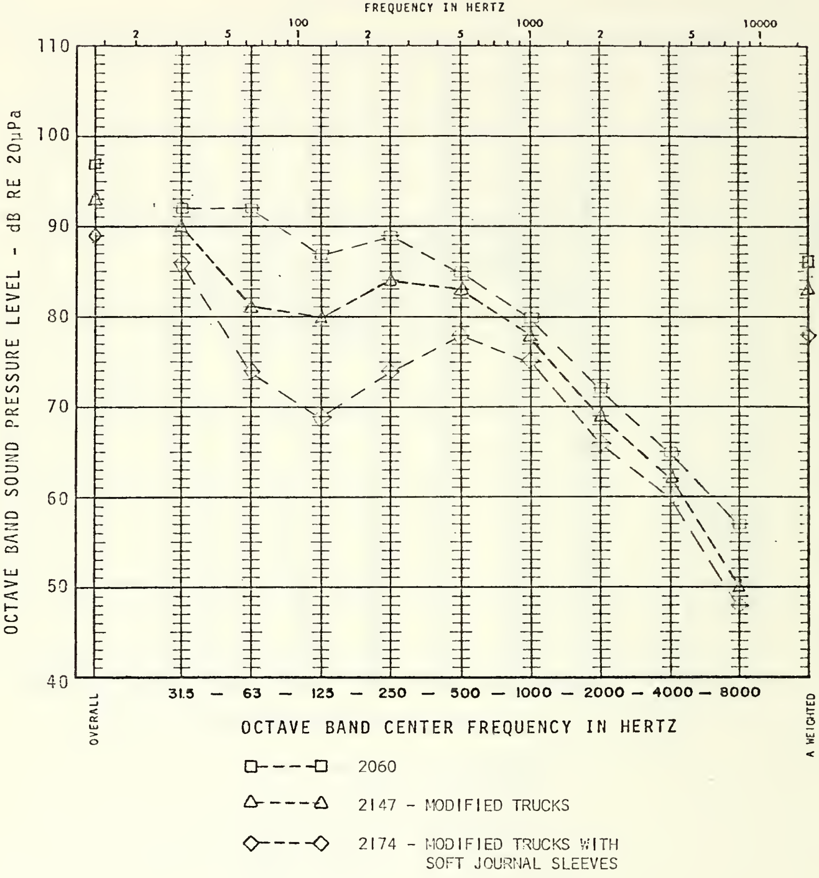


FIGURE F16 AVERAGE CAR INTERIOR NOISE LEVELS WHEN PASSING THROUGH A ROUND TUNNEL STATION WITH BALLAST & TIE TRACK

30 MPH

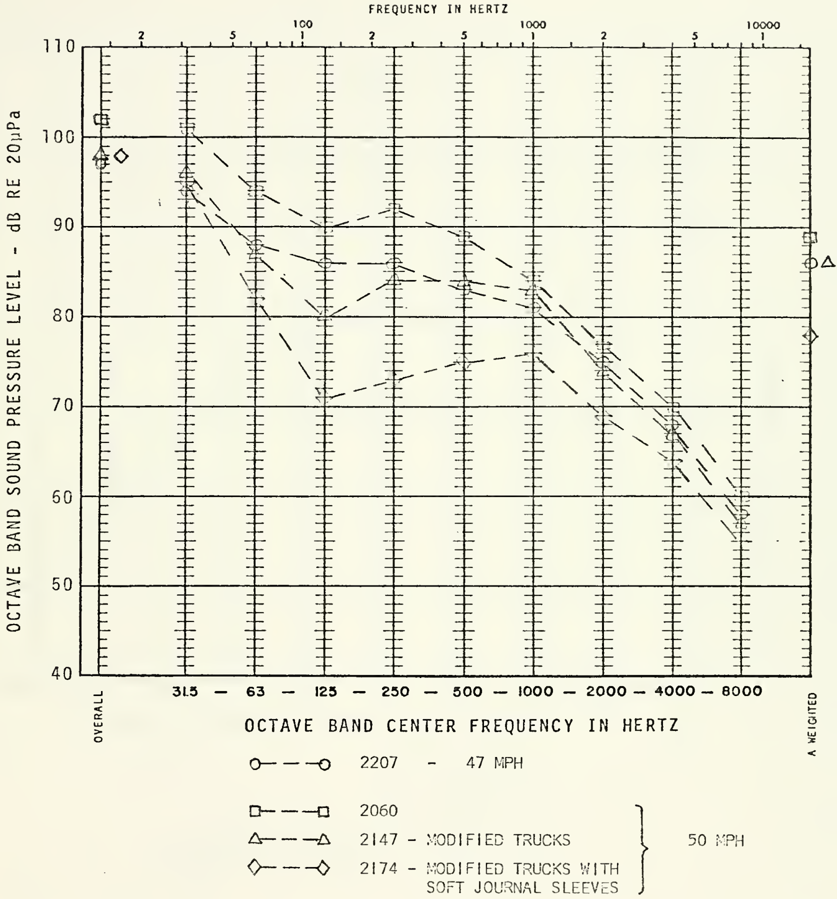


FIGURE F17 AVERAGE CAR INTERIOR NOISE LEVELS WHEN PASSING THROUGH A BOX SECTION STATION WITH BALLAST & TIE TRACK

50 MPH

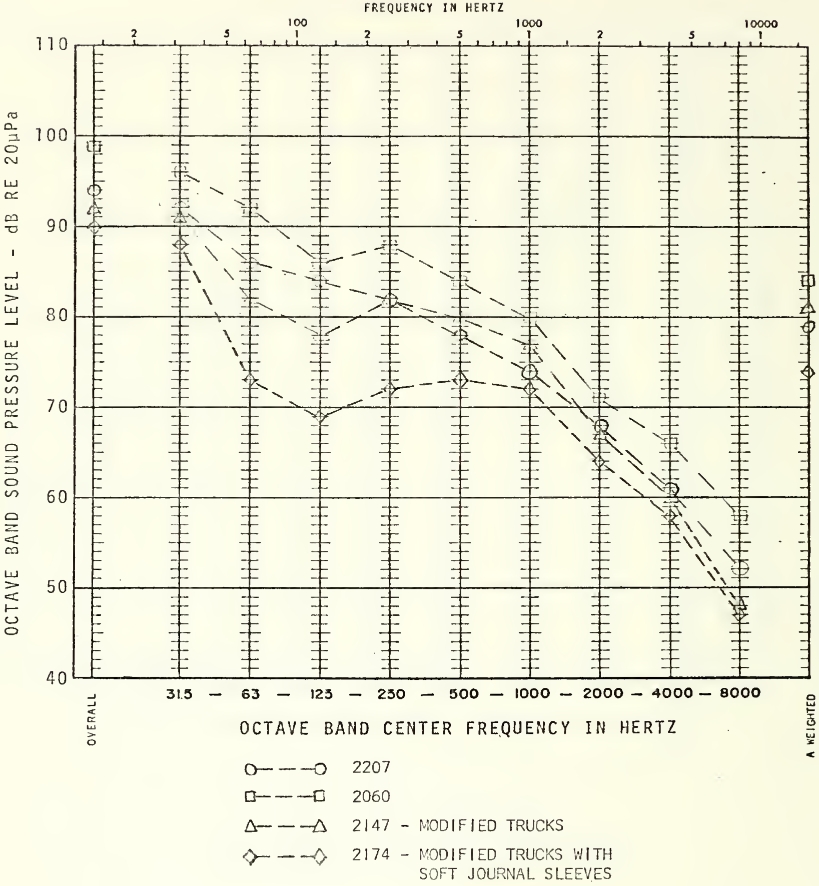


FIGURE F18 AVERAGE CAR INTERIOR NOISE LEVELS WHEN PASSING THROUGH A BOX SECTION STATION WITH BALLAST & TIE TRACK

30 MPH

APPENDIX G

WAYSIDE AND CAR INTERIOR NOISE LEVELS FOR CAR EQUIPMENT

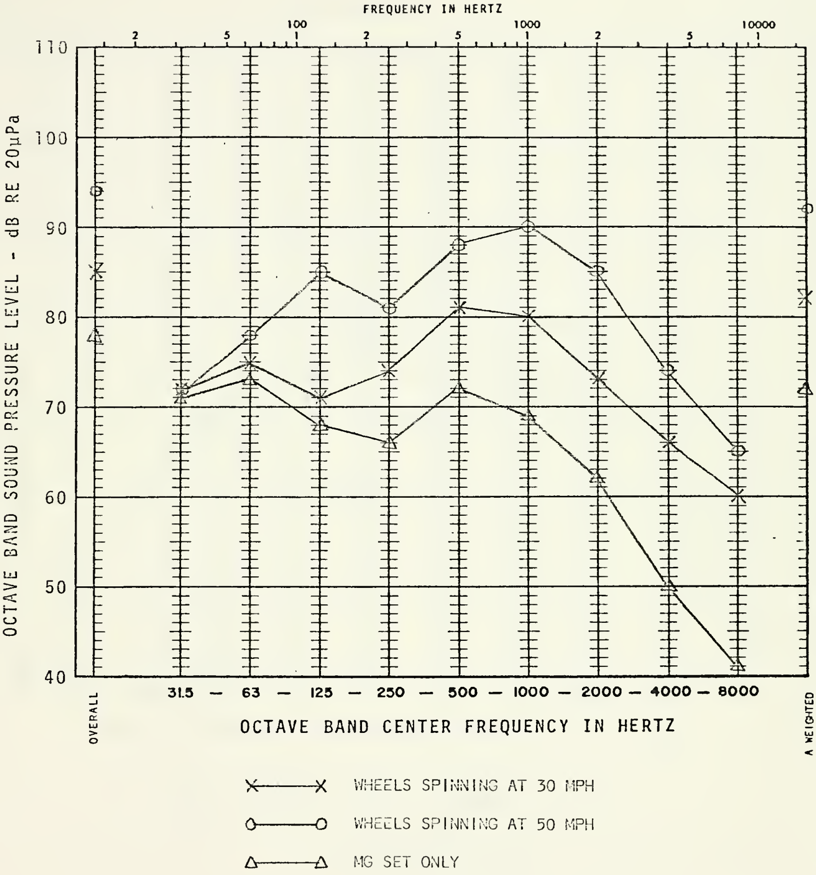


FIGURE G1 CAR 6624 EQUIPMENT WAYSIDE NOISE - CAR ON JACKS IN SHOP

25 FT FROM CAR CENTERLINE

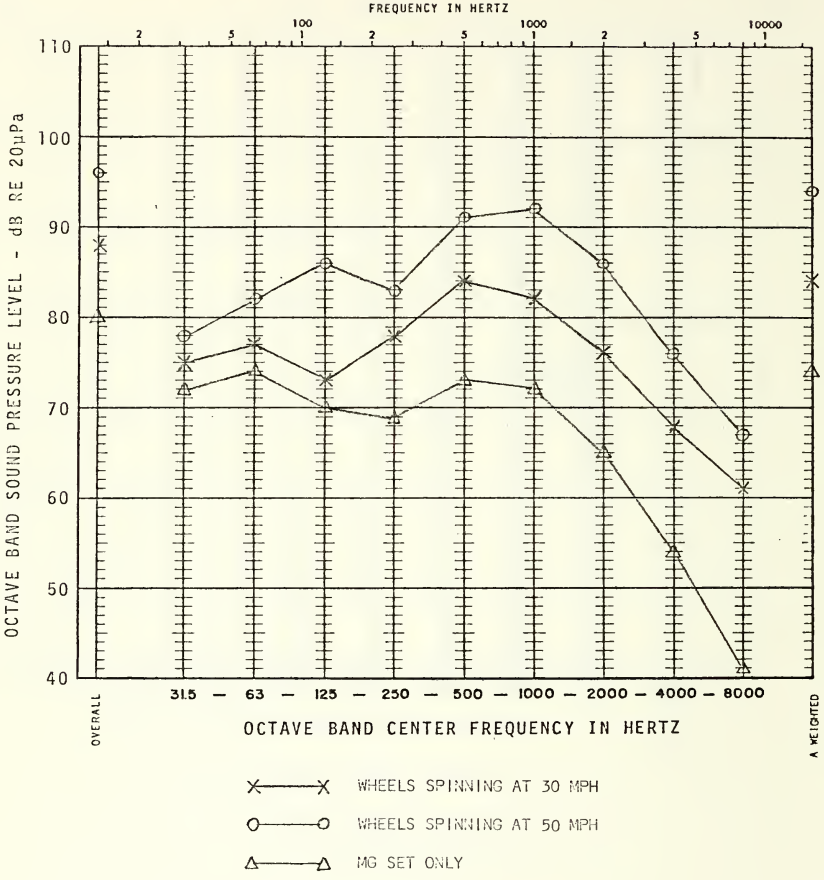


FIGURE G2 CAR 6624 EQUIPMENT WAYSIDE NOISE - CAR ON JACKS IN SHOP

15 FT FROM CAR CENTERLINE

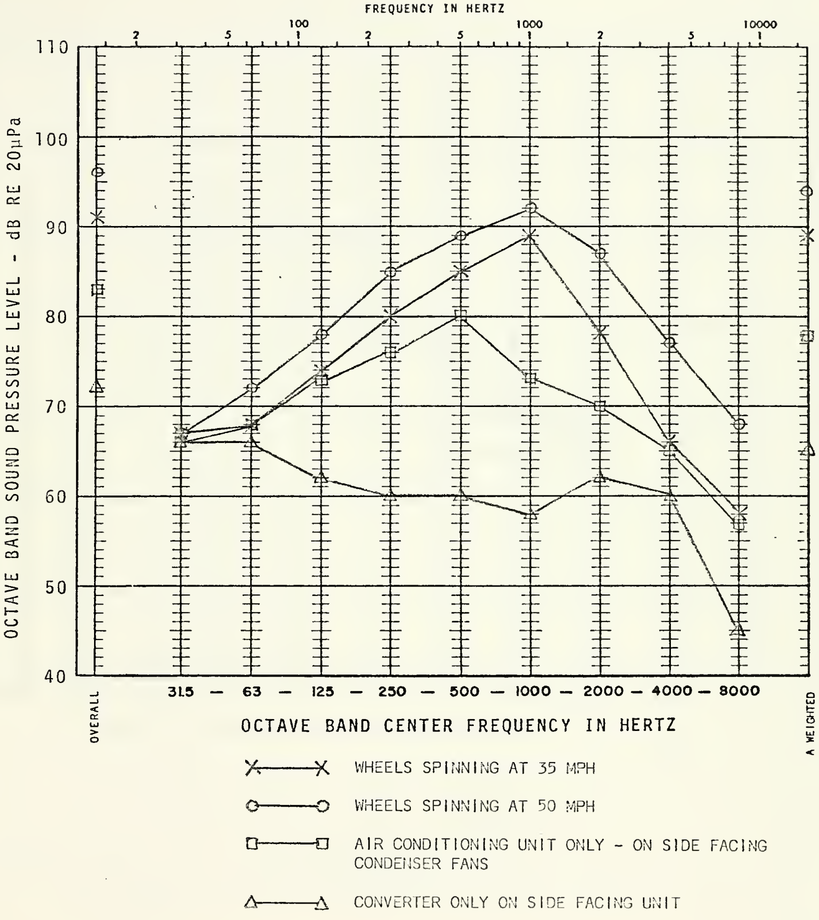


FIGURE G3 CAR 2207 EQUIPMENT WAYSIDE NOISE - CAR ON JACKS IN SHOP

25 FT FROM CAR CENTERLINE

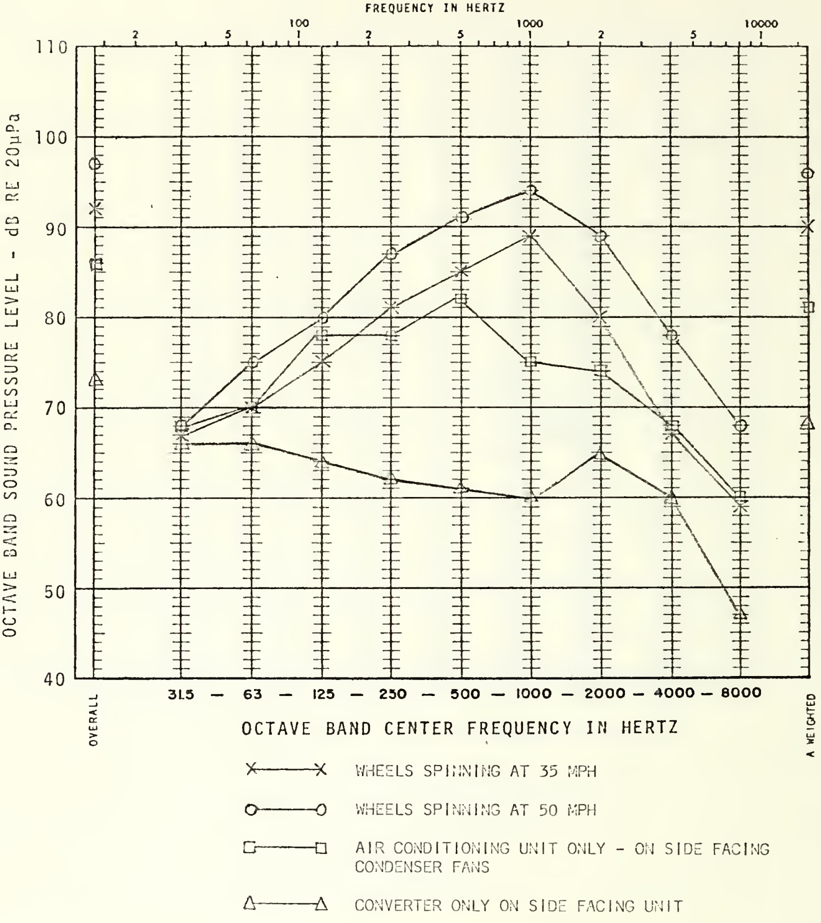


FIGURE G4 CAR 2207 EQUIPMENT WAYSIDE NOISE - CAR ON JACKS IN SHOP

15 FT FROM CAR CENTERLINE

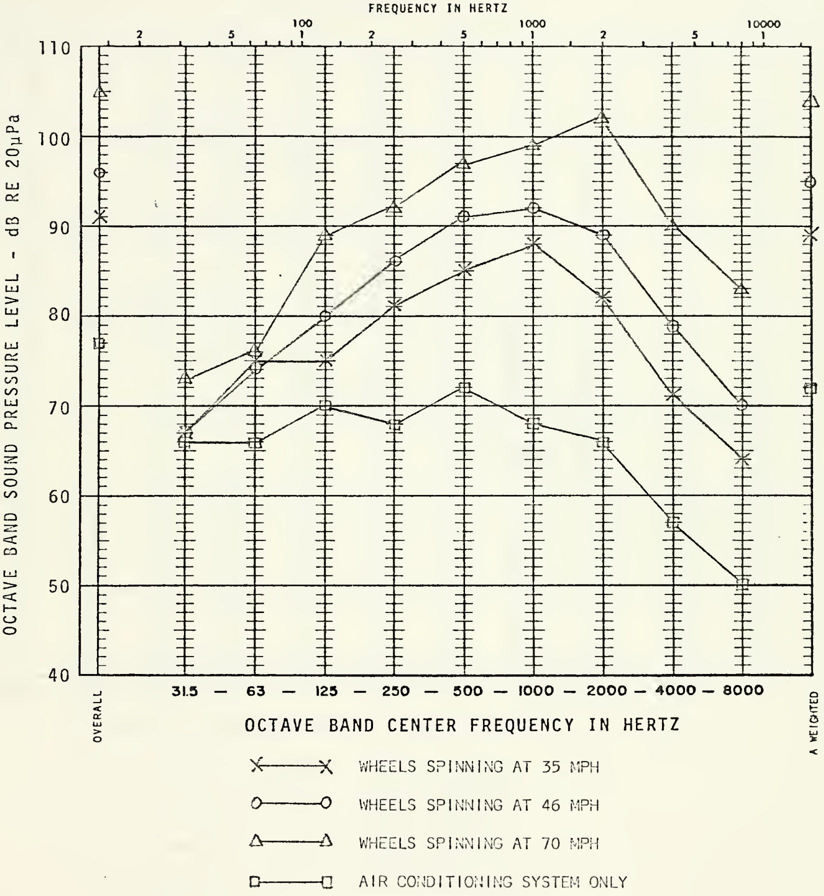


FIGURE G5 CAR 2060 EQUIPMENT WAYSIDE NOISE - CAR ON JACKS IN SHOP

25 FT FROM CAR CENTERLINE

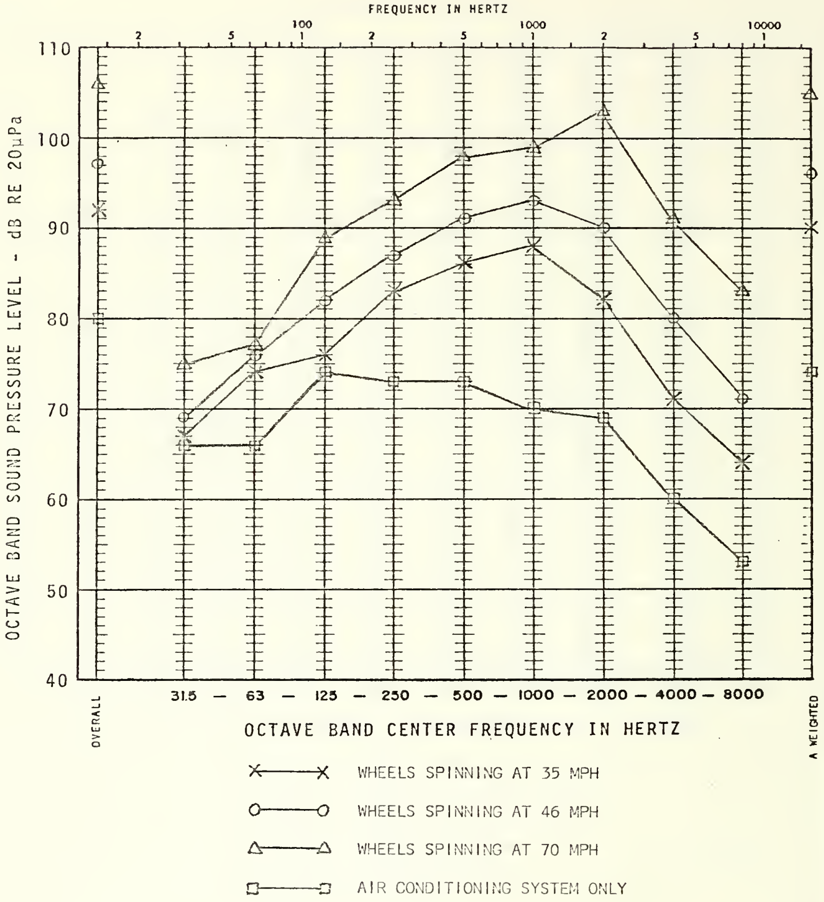


FIGURE G6 CAR 2060 EQUIPMENT WAYSIDE NOISE - CAR ON JACKS IN SHOP

15 FT FROM CAR CENTERLINE

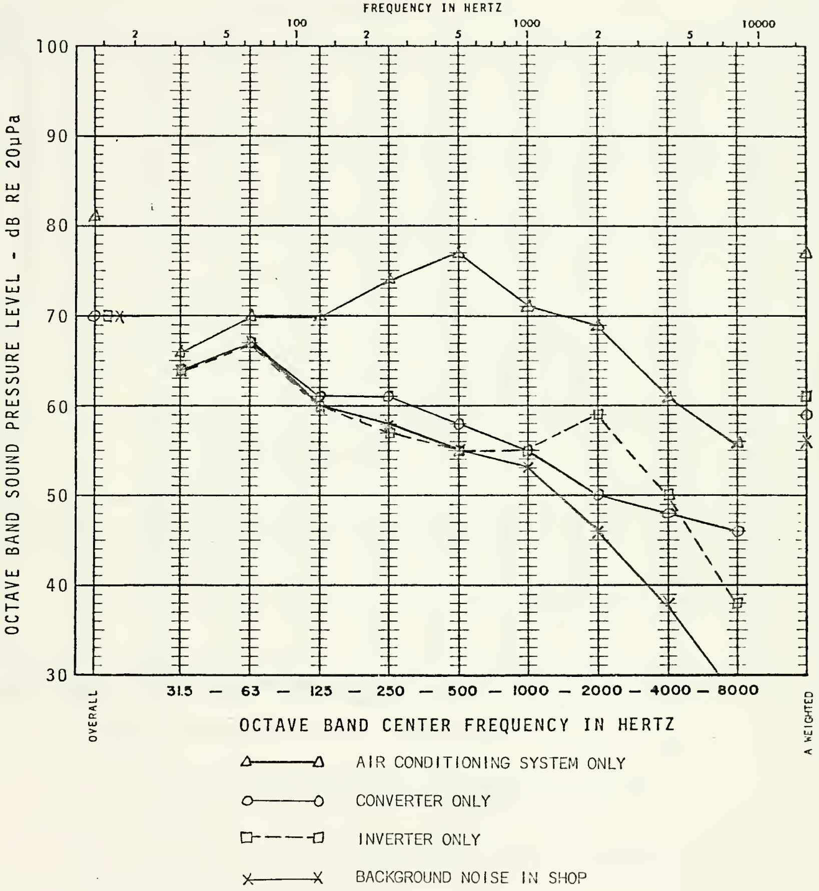


FIGURE G7 CAR 2059 EQUIPMENT WAYSIDE NOISE - CAR ON JACKS IN SHOP

25 FT FROM CAR CENTERLINE

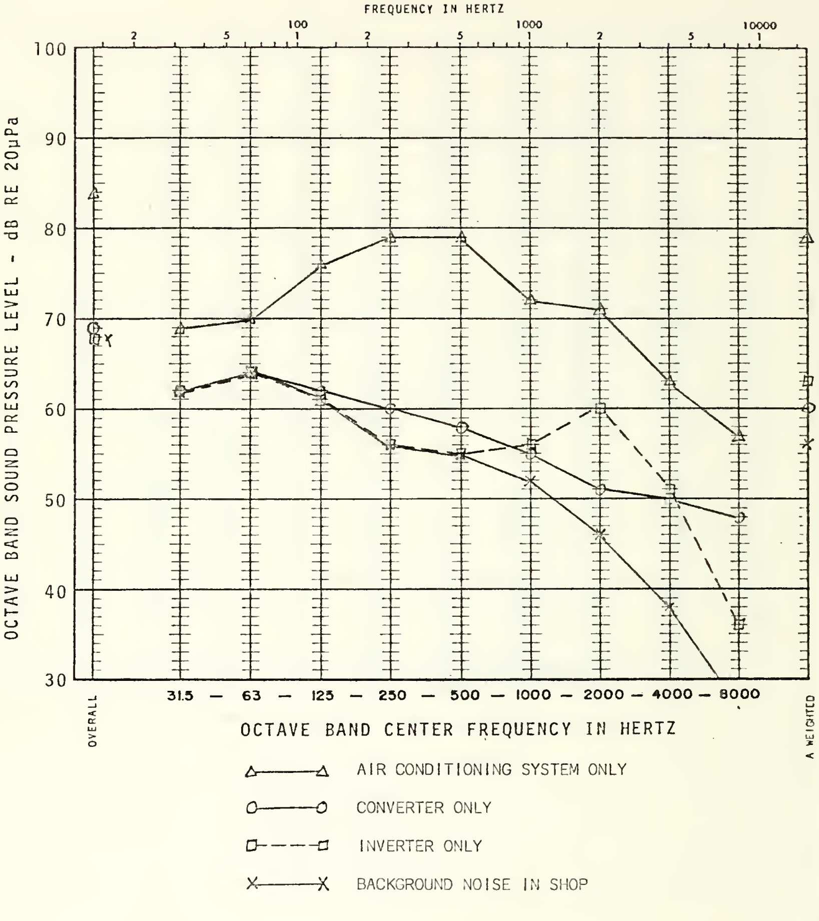


FIGURE G8 CAR 2059 EQUIPMENT WAYSIDE NOISE - CAR ON JACKS IN SHOP

15 FT FROM CAR CENTERLINE

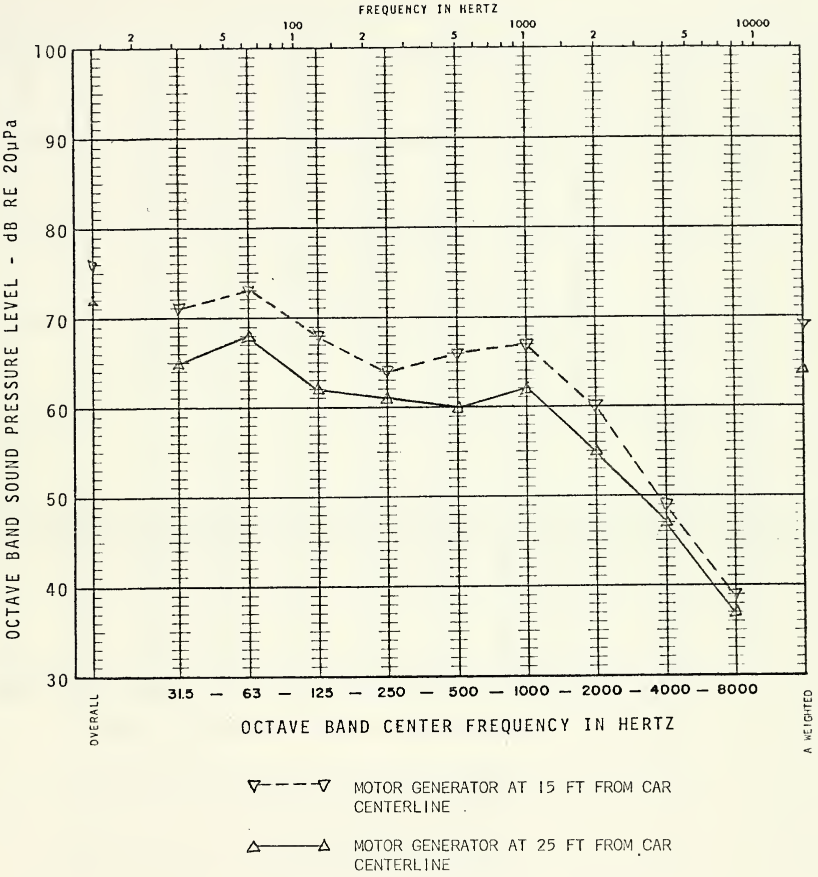
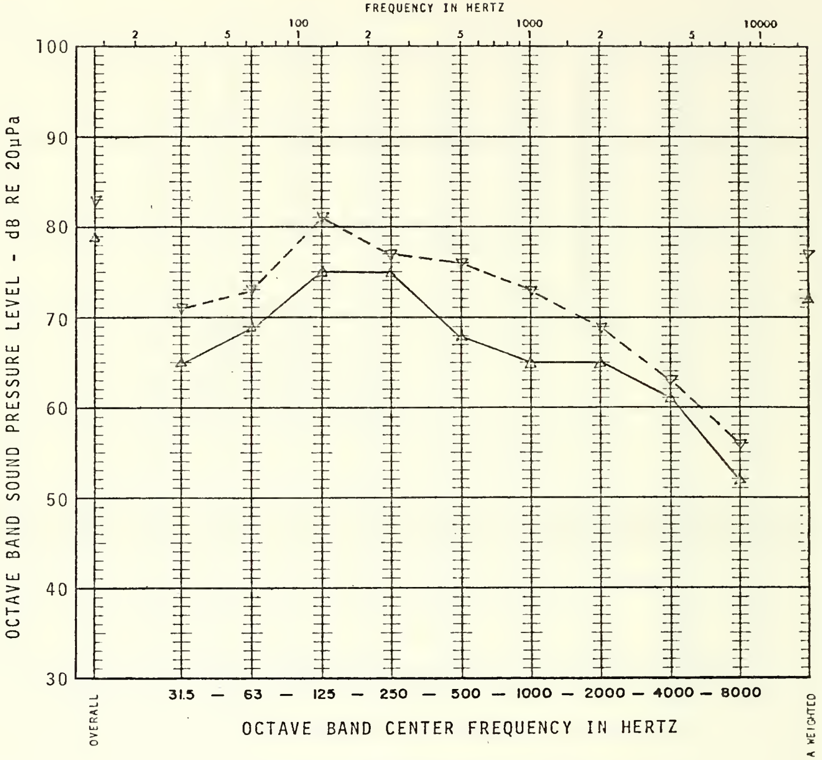


FIGURE G9 CAR 6624 EQUIPMENT NOISE - CAR PARKED ON BALLAST AND TIE TRACKS OUTSIDE SHOP



▽- - - -▽ AIR CONDITIONING UNIT AT 15 FT FROM CAR CENTERLINE

△———△ AIR CONDITIONING UNIT AT 25 FT FROM CAR CENTERLINE

FIGURE G10 CAR 2207 EQUIPMENT NOISE - CAR PARKED ON BALLAST AND TIE TRACKS OUTSIDE SHOP

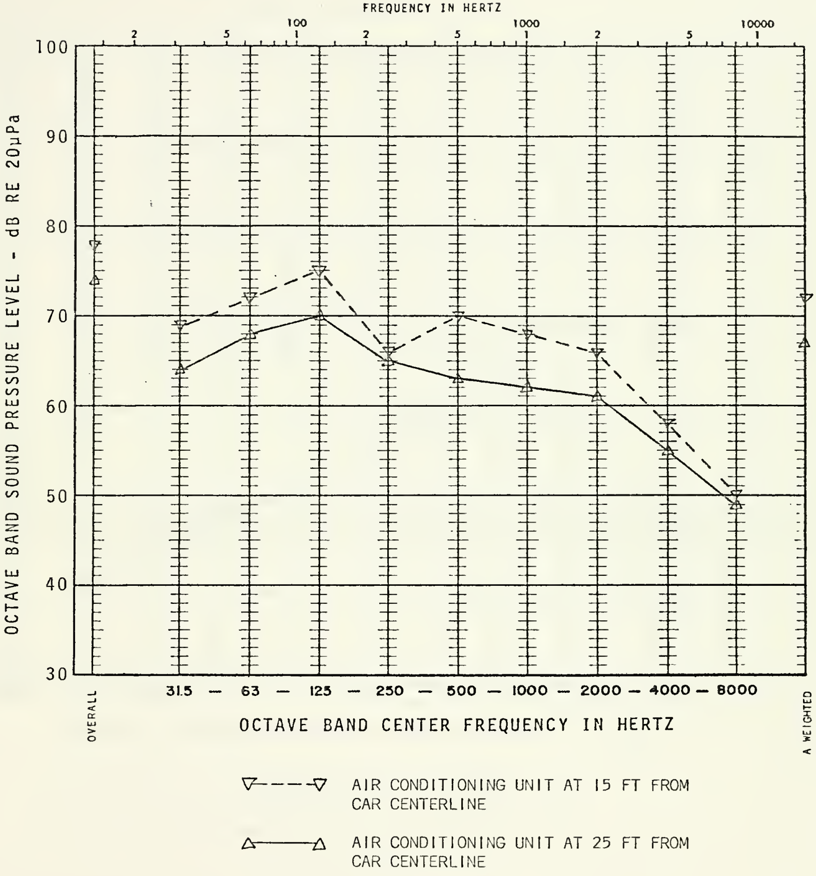


FIGURE G11 CAR 2060 EQUIPMENT NOISE - CAR PARKED ON BALLAST AND TIE TRACKS OUTSIDE SHOP

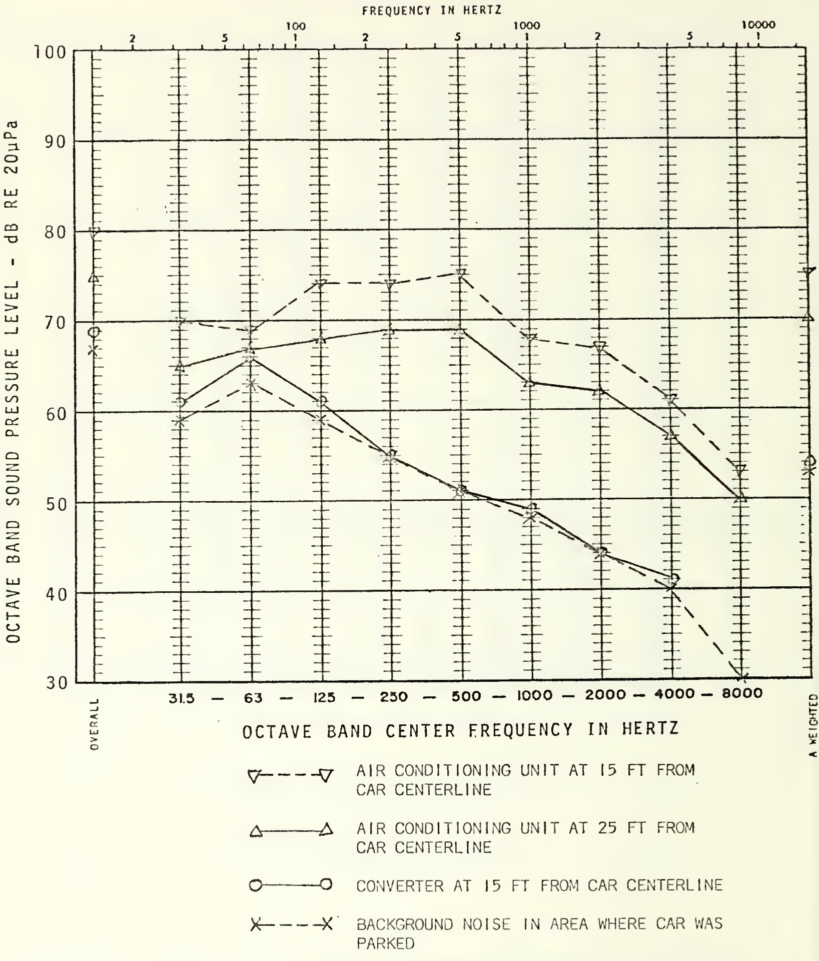


FIGURE G12 CAR 2059 EQUIPMENT NOISE - CAR PARKED ON BALLAST AND TIE TRACKS OUTSIDE SHOP

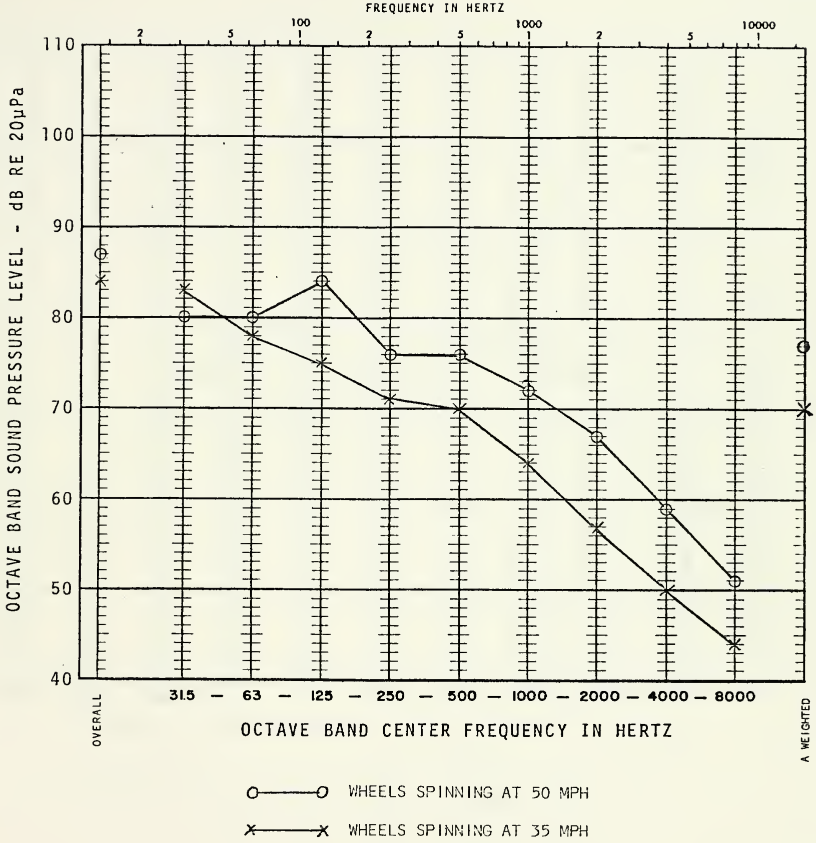


FIGURE G13 CAR 6624 AVERAGE INTERIOR NOISE - CAR ON JACKS IN SHOPS

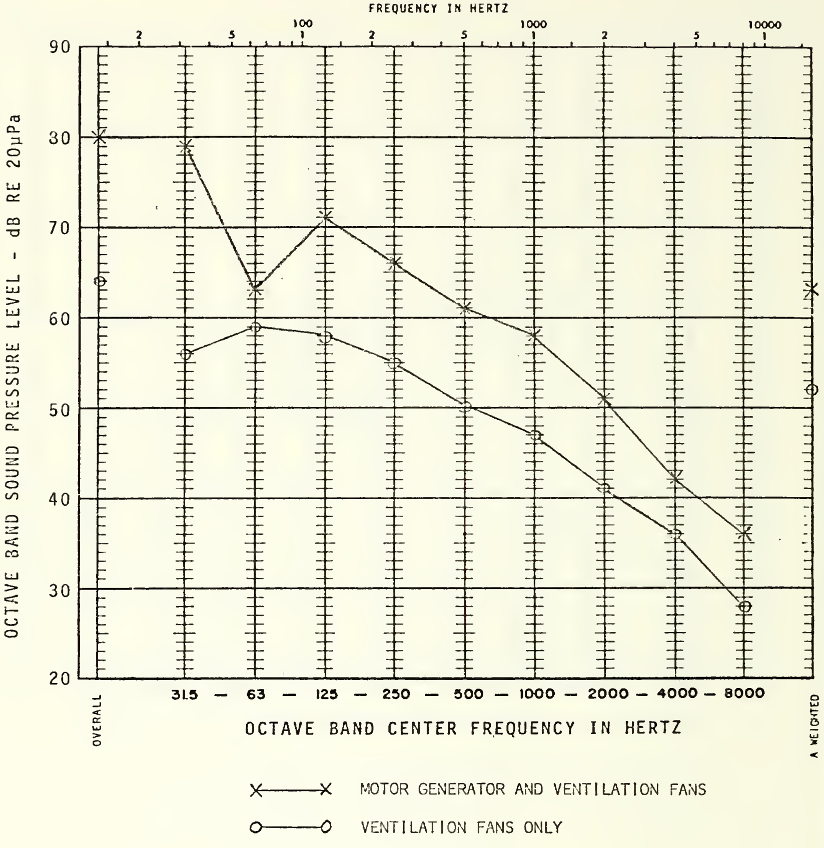


FIGURE G14 CAR 6624 AVERAGE INTERIOR NOISE - CAR ON JACKS IN SHOP

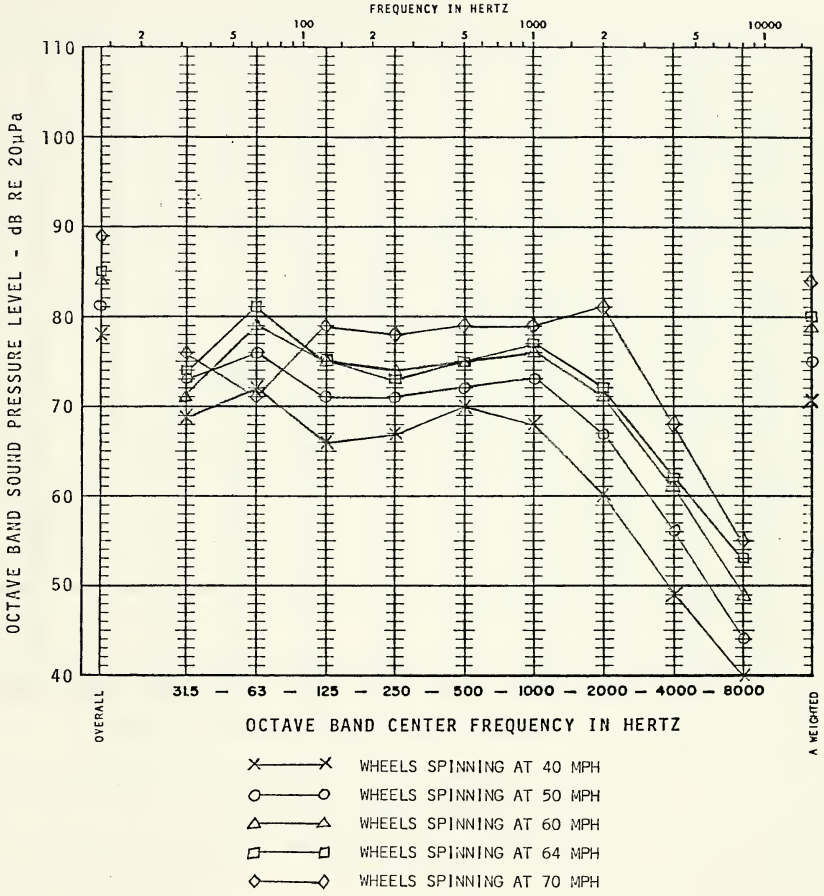


FIGURE G15 CAR 2207 AVERAGE INTERIOR NOISE - CAR ON JACKS IN SHOP

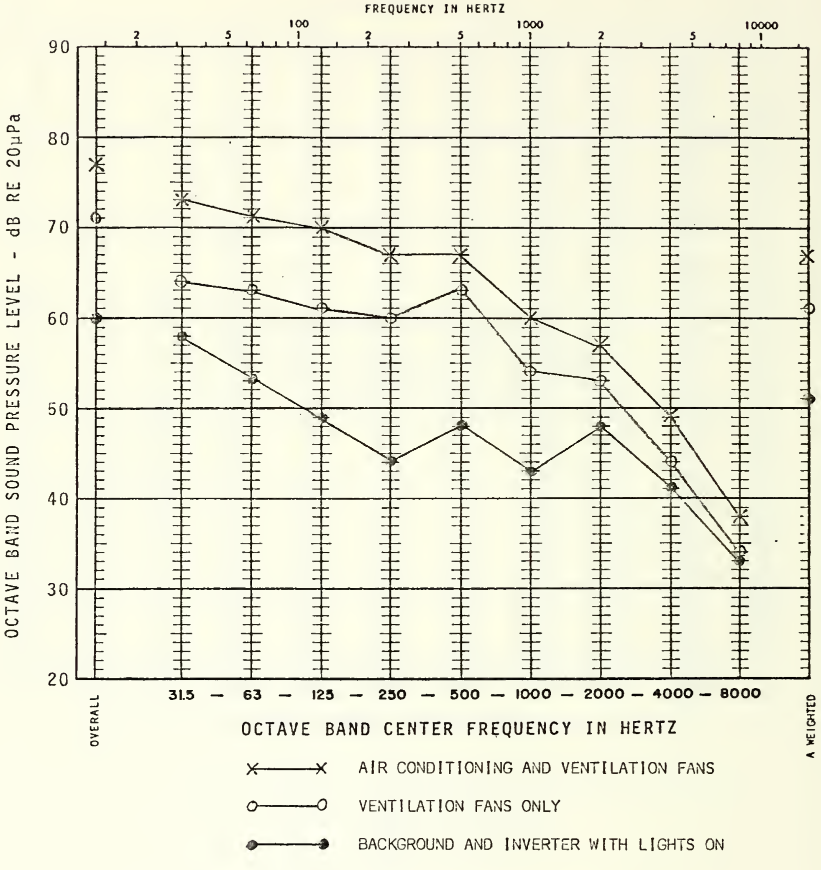


FIGURE G16 CAR 2207 AVERAGE INTERIOR NOISE - CAR ON JACKS IN SHOP

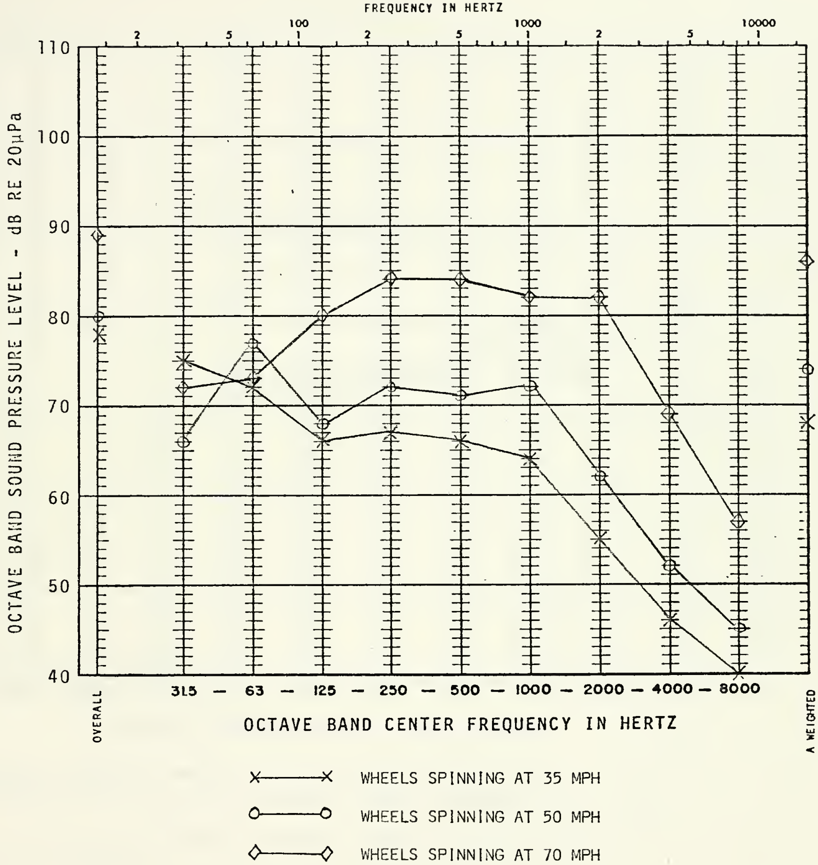


FIGURE G17 CAR 2060 AVERAGE INTERIOR NOISE - CAR ON JACKS IN SHOP

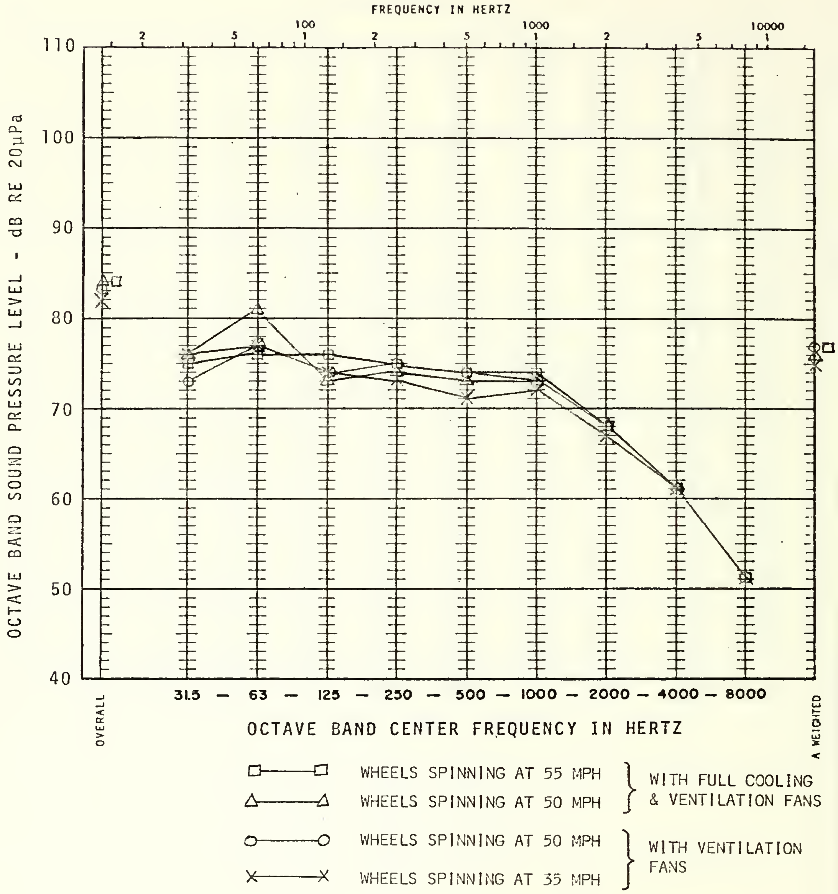


FIGURE G18 CAR 2060 AVERAGE INTERIOR NOISE - CAR ON JACKS IN SHOP

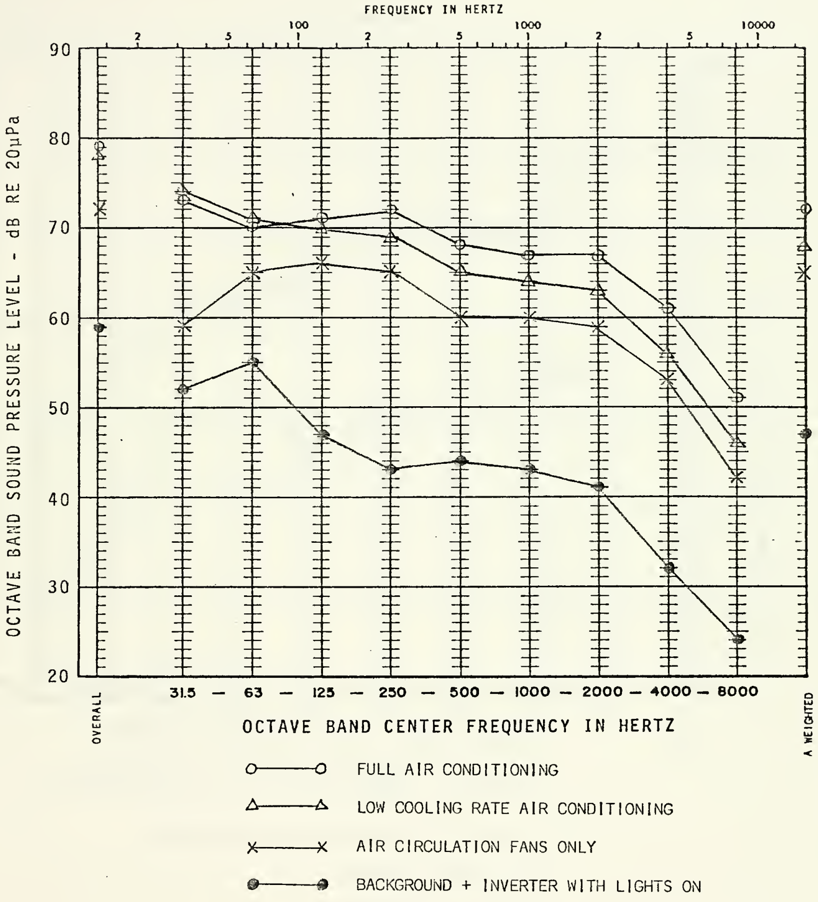


FIGURE G19 CAR 2060 AVERAGE INTERIOR NOISE - CAR ON JACKS IN SHOP

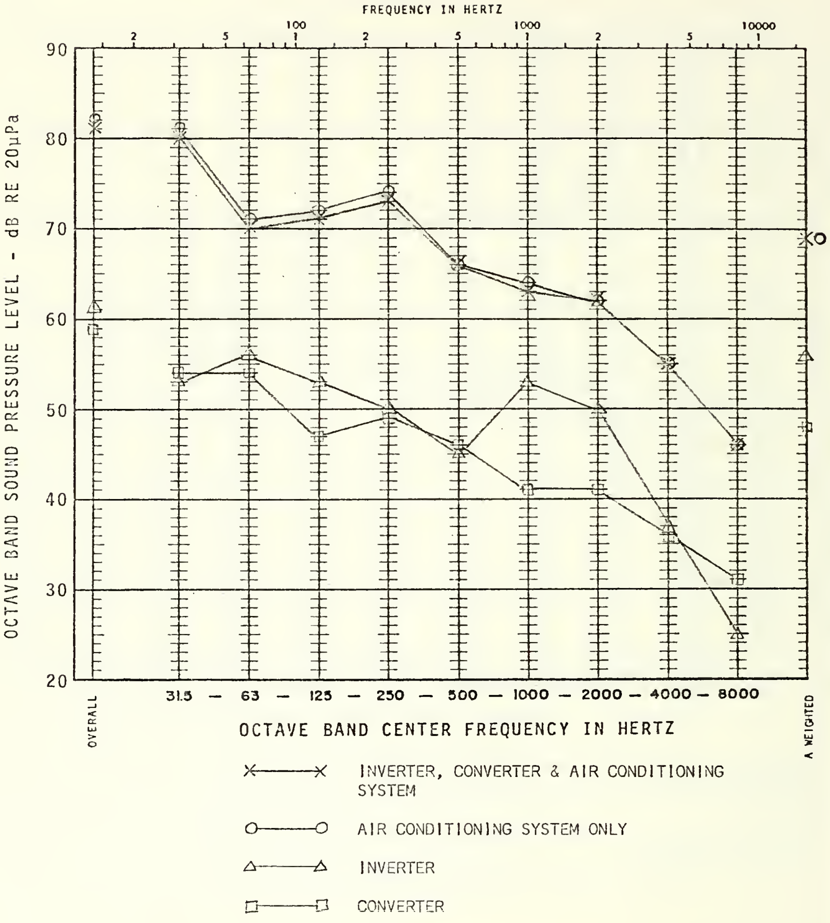


FIGURE G20 CAR 2059 AVERAGE INTERIOR NOISE - CAR ON JACKS IN SHOP